

## ARTICLES

Measurement of the ratio  $\sigma B(p\bar{p} \rightarrow W \rightarrow e\nu)/\sigma B(p\bar{p} \rightarrow Z^0 \rightarrow ee)$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1800$  GeV

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We present an analysis of data from  $p\bar{p}$  collisions at a center-of-mass energy of  $\sqrt{s} = 1800$  GeV. A measurement is made of the ratio  $R \equiv \sigma B(p\bar{p} \rightarrow W \rightarrow e\nu) / \sigma B(p\bar{p} \rightarrow Z^0 \rightarrow ee)$ . The data represent  $19.6 \text{ pb}^{-1}$  collected by the Collider Detector at Fermilab during the 1992–1993 collider run of the Fermilab Tevatron. We find  $R = 10.90 \pm 0.32(\text{stat}) \pm 0.29(\text{syst})$ , and from this value we extract a measurement of the  $W \rightarrow e\nu$  branching ratio  $\Gamma(W \rightarrow e\nu) / \Gamma(W) = 0.1094 \pm 0.0033(\text{stat}) \pm 0.0031(\text{syst})$ . From this branching ratio we set a limit on the top quark mass of  $m_t > 62 \text{ GeV}/c^2$  at the 95% confidence level. In contrast with direct searches for the top quark, this limit makes no assumptions about the allowed decay modes of the top quark. In addition, we use a calculation of the leptonic width  $\Gamma(W \rightarrow e\nu)$  to obtain a value for the  $W$  total decay width:  $\Gamma(W) = 2.064 \pm 0.060(\text{stat}) \pm 0.059(\text{syst}) \text{ GeV}$ .

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## I. INTRODUCTION

The  $W$  boson width  $\Gamma(W)$  is a fundamental parameter that is well predicted in the standard model. The  $W$  decays with approximately equal probability to each of three lepton families and to the two quark families that are kinematically available. The quark families receive an additional factor of 3 in their decay probabilities due to their color charge. Hence the branching ratio of the  $W$

into  $(l, \bar{\nu}_l)$  is approximately  $\frac{1}{9}$ . By dividing a calculation of the  $W$  leptonic partial width  $\Gamma(W \rightarrow l\nu)$  by the leptonic branching ratio, one may predict that the  $W$  width is  $\approx 2.1 \text{ GeV}$ . This article presents a measurement of  $W$  boson decay width  $\Gamma(W)$  and of the leptonic branching ratio  $\Gamma(W \rightarrow e\nu) / \Gamma(W)$ .

The  $W$  width is altered if additional decay modes are available to the  $W$ . In particular, if the  $W$  can decay to a light top quark ( $m_t < M_W - m_b$ ) and a  $b$  quark, the  $W$  width changes to  $\Gamma(W) \approx 2.8 \text{ GeV}$  and the leptonic

branching ratio changes to  $\Gamma(W \rightarrow \nu)/\Gamma(W) \approx 1/12$ . Direct searches [1] have set a limit of  $m_t > 131 \text{ GeV}/c^2$  (95% C.L.), but these limits assume that the top quark always decays via the reaction  $t \rightarrow Wb$ . We have presented evidence [2] that suggests that the top quark mass is  $m_t = 174 \pm 17 \text{ GeV}/c^2$ . If, however, the top quark is light and has decays other than  $t \rightarrow Wb$  that have been missed by the direct searches, or if other weak isodoublets exist that couple to the  $W$ , then the  $W$  width could see a contribution from these sources. The top quark could have nonstandard model decays, for example, if a charged Higgs boson exists and  $t \rightarrow H^+b$  were the dominant decay channel. Then the top quark could be missed by direct searches for  $t \rightarrow Wb$  [3]. These enhancements to the  $W$  width are independent of assumptions regarding the allowed decays of the daughters of the  $W$ .

The  $W$  decays with universal coupling to pairs of fermions within weak isodoublets. The partial width into fermion pairs is calculated to be [4]  $\Gamma_0(W \rightarrow f\bar{f}) = |V_{ff'}|^2 N_c g^2 M_W / 48\pi$ , where  $V_{ff'}$  is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element for two quarks and is 1.0 for leptons. The color factor  $N_c$  is 3 for quarks and is 1 for leptons. The variable  $M_W$  is the  $W$  boson mass, and  $g$  is the  $W$ 's coupling to fermions. In the standard model the  $W$ -fermion coupling is given by  $g^2 = \frac{8}{\sqrt{2}} G_F M_W^2$ , where  $G_F$  is the Fermi coupling constant derived from the muon lifetime.

This simple calculation of the  $W$  width receives corrections at next-to-leading order in QCD. At lowest order, the  $W$  may decay with equal probability to each of three lepton families and to two quark families, assuming that the top quark is heavy (with a color factor of 3 on the quark decays). Quark decays receive an additional QCD  $K$ -factor enhancement at  $O(\alpha_s)$  due to vertex graphs involving gluon exchange. Rosner *et al.* [5] have thus calculated

$$\Gamma_0(W \rightarrow \nu)/\Gamma_0(W) = \{3 + 6[1 + \alpha_s(M_W)/\pi]\}^{-1} \\ = 0.1084 \pm 0.0002 ,$$

$$\Gamma_0(W) = 2.075 \pm 0.021 \text{ GeV} .$$

The  $W$  width also receives electroweak corrections due to next-to-leading order graphs which alter the effective coupling  $g$  at the  $W$ -fermion vertex for all fermions. Within the context of the standard model the  $W$  width receives vertex and bremsstrahlung corrections [4] that depend upon the top quark and Higgs boson masses. The corrections can be summarized in the equation

$$\Gamma(W \rightarrow f\bar{f})_{\text{SM}} = \Gamma_0(W \rightarrow f\bar{f})[1 + \delta_V + \delta_W(0) + \delta_\mu] ,$$

where  $\delta_W(0)$  is the correction to the width from loops at the  $W$ -fermion vertex involving  $Z^0$ 's or a standard model Higgs boson,  $\delta_V$  describes boson self-energies, and  $\delta_\mu$  is a correction made necessary when  $g$  is parametrized using the  $W$  mass and the value of  $G_F$  from muon decay [6]. The factor  $\delta_W(0)$  also incorporates corrections to the  $W$  propagator from the top quark that are not absorbed into the  $W$  mass. The vertex corrections from the standard model Higgs boson cause  $\Gamma(W)$  to change by approximately 1% as the Higgs boson mass varies from 50 to

1000  $\text{GeV}/c^2$ , while the correction from  $t\bar{b}$  loops changes  $\Gamma(W)$  by approximately 4% as the top quark mass varies from 80 to 200  $\text{GeV}/c^2$  [4].

Because the electroweak vertex corrections to  $g$  above are nearly identical for both leptons and quarks, these corrections affect only the  $W$  width. In the case of the leptonic branching ratio, the coupling  $g$  cancels out and hence the leptonic branching ratio is almost completely insensitive to these vertex corrections. Including the radiative corrections, and for the particular choice of  $m_t = 140 \text{ GeV}/c^2$  and  $M_{\text{Higgs}} = 100 \text{ GeV}/c^2$ , Rosner *et al.* find [5]

$$\Gamma(W)_{\text{SM}} = 0.996 \times \Gamma_0(W) = 2.067 \pm 0.021 \text{ GeV} ,$$

$$\Gamma(W \rightarrow \nu)_{\text{SM}}/\Gamma(W)_{\text{SM}} = \Gamma_0(W \rightarrow \nu)/\Gamma_0(W) \\ = 0.1084 \pm 0.0002 .$$

To test the standard model, it is desirable to measure both  $\Gamma(W \rightarrow \nu)/\Gamma(W)$  and  $\Gamma(W)$ . The branching ratio is the most sensitive quantity for new decay modes, since the uncertainty in the theoretical prediction of  $\Gamma(W)$  due to the uncertainty in the measured  $W$  mass cancels in the branching ratio. The total width, furthermore, may be used along with the leptonic branching ratio to obtain a measure of  $\Gamma(W \rightarrow \nu)$ . The leptonic partial width is predicted to be  $g^2 M_W / 48\pi$ , and deviations in the measured value indicate values of the  $W$ -fermion coupling  $g^2$  different from that given by the standard model.

#### A. Measurement of $\Gamma(W)$ from $W$ and $Z^0$ cross sections

The  $W$  leptonic branching ratio may be extracted from a measurement of the ratio,  $R$ , of the cross sections times leptonic branching ratios of the  $W$  and  $Z^0$  in  $p\bar{p}$  collisions [7]. The ratio  $R$  may be expressed as

$$R \equiv \frac{\sigma B(p\bar{p} \rightarrow W \rightarrow \nu)}{\sigma B(p\bar{p} \rightarrow Z^0 \rightarrow l\bar{l})} \\ = \frac{\sigma(p\bar{p} \rightarrow W) \Gamma(W \rightarrow \nu) \Gamma(Z^0)}{\sigma(p\bar{p} \rightarrow Z^0) \Gamma(Z^0 \rightarrow l\bar{l}) \Gamma(W)} .$$

On the right-hand side, the ratio  $\sigma(p\bar{p} \rightarrow W)/\sigma(p\bar{p} \rightarrow Z^0)$  of the production cross sections may be calculated from the boson couplings and knowledge of the proton structure. The  $Z^0$  total width  $\Gamma(Z^0)$  and the leptonic partial width  $\Gamma(Z^0 \rightarrow l^+l^-)$  are well measured by the experiments at the CERN  $e^+e^-$  collider LEP [8]. Thus a measurement of  $R$  yields a precise measurement of the  $W$  leptonic branching ratio  $\Gamma(W \rightarrow \nu)/\Gamma(W)$ . If one then divides a calculation of the leptonic width  $\Gamma(W \rightarrow \nu)$  by the measured branching ratio, a value is extracted for the total decay width  $\Gamma(W)$  of the  $W$ . Note, however, that the width extracted from the branching ratio is not sensitive to electroweak vertex corrections to the coupling  $g$ , since it is normalized to the calculated  $\Gamma(W \rightarrow \nu)$ . While in principle the corrections to the  $W$ -fermion coupling would also alter the production cross section  $\sigma(p\bar{p} \rightarrow W)$ , a direct measurement of  $\Gamma(W)$ , such

as the one described in Sec. IB, is desirable as a check of these effects.

### B. Previous measurements of $\Gamma(W)$

The measurements of the  $W$  width extracted from the ratio  $R$  are given in Table I. In Table I, mode = “ $e$ ” or “ $\mu$ ” refers to the decay mode of the  $W$  (or  $Z^0$ ) used in the measurement. This long paper reports on a measurement of  $R$  made by the Collider Detector at Fermilab (CDF) Collaboration [9] with a relative uncertainty of 4.1%. The best measurement of the  $W$  width previous to the most recent CDF result has an error of 7.6%. The combination of all published measurements from  $R$  yields a value for the  $W$  total decay width,  $\Gamma(W) = 2.07 \pm 0.07$  GeV, an accuracy of 3.5%. Prior to the most recent CDF measurement, the world average had an uncertainty of 5.2%.

The  $W$  width has also been measured directly [15] from studies of the  $W$  transverse mass line shape in  $p\bar{p}$  collisions, where  $M_T^2 \equiv (|\vec{p}_T^e| + |\vec{p}_T^\nu|)^2 - (\vec{p}_T^e + \vec{p}_T^\nu)^2$  and  $\vec{p}_T^e$  and  $\vec{p}_T^\nu$  are components of the electron and neutrino transverse to the  $p$  and  $\bar{p}$  beams. These direct measurements complement the indirect value from the  $W$  and  $Z^0$  cross sections because they have entirely different systematic uncertainties. More importantly, they are free of the theoretical assumptions regarding the  $W$  coupling to fermions. Direct measurements of  $\Gamma(W)$  from the transverse mass distribution at hadron colliders will approach the 1% level with the anticipated  $1 \text{ fb}^{-1}$  of data at Fermilab in the future [16].

The  $W$  width will also be determined by the LEP-200 experiments at center-of-mass energy near  $\sqrt{s} = 2M_W$  from an end-point analysis of the  $W$  daughter lepton energy spectrum. This measurement of  $\Gamma(W)$  is also a direct one, like the line shape measurements at  $p\bar{p}$  colliders, and the LEP-200 experiments anticipate an accuracy of  $\Gamma(W)$  of 200 MeV, or 10% [17].

### C. 1992–1993 run of CDF

The data presented in this paper were collected by the Collider Detector at Fermilab observing  $p\bar{p}$  collisions at a center of mass energy of  $\sqrt{s} = 1.8$  TeV. During the 1992–1993 collider run, the Fermilab Tevatron delivered a total integrated luminosity of  $\int L dt = 27.3 \text{ pb}^{-1}$ , with typical

instantaneous luminosities of  $4.0 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$  and a peak instantaneous luminosity of  $9.7 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ . The Collider Detector at Fermilab wrote  $20.6 \text{ pb}^{-1}$  of data to tape, with the 30% loss dominated by operational problems. This compares to  $4.0 \text{ pb}^{-1}$  of data collected in CDF's previous 1988–1989 run. Approximately  $1.0 \text{ pb}^{-1}$  of this year's data was discarded after the fact because of hardware difficulties during data taking. In the  $19.6 \text{ pb}^{-1}$  of data remaining, approximately 20 000  $W \rightarrow e\nu$  and 1600  $Z^0 \rightarrow e^+e^-$  decays were observed from all triggers, as were 7000  $W \rightarrow \mu\nu$  and 600  $Z^0 \rightarrow \mu^+\mu^-$  decays. Note that, while same data sample is being reported on as in Ref. [9], our measurement of the luminosity has changed by approximately 10%. This change is documented in Ref. [2]. Thus, while Ref. [9] quotes an integrated luminosity of  $21.7 \text{ pb}^{-1}$ , that same data sample is here estimated as consisting of  $19.6 \text{ pb}^{-1}$ . Note that  $R$  is independent of the luminosity.

### D. Strategy of this measurement

The signature of high- $P_T$  leptons from  $W$  and  $Z^0$  decay is quite distinctive in the environment of hadron collisions. As such, the decay of  $W$  and  $Z^0$  bosons into leptons provides a clean experimental measurement of their production. Experimentally, the cross sections times branching ratios are found from

$$\sigma B(p\bar{p} \rightarrow W \rightarrow l\nu) = \frac{N_{\text{candidates}} - N_{\text{background}}}{A_W \epsilon_W \int L dt},$$

$$\sigma B(p\bar{p} \rightarrow Z^0 \rightarrow l^+l^-) = \frac{N_{\text{candidates}} - N_{\text{background}}}{A_Z \epsilon_Z \int L dt},$$

where  $N_{\text{candidates}}^W$  and  $N_{\text{candidates}}^Z$  are the number of  $W$  and  $Z^0$  candidates observed,  $A_W$  and  $A_Z$  are the “acceptance” for the  $W$  and  $Z^0$  decays (which includes the efficiency for the kinematic cuts on the leptons and the geometric acceptance of the detector),  $\epsilon_W$  and  $\epsilon_Z$  are the efficiency for the  $W$  and  $Z^0$  to pass the lepton identification criteria, and  $\int L dt$  is the integrated luminosity of the experiment. Measuring the ratio of the cross sections allows some of the quantities (as well as their uncertainties) on the right-hand sides to cancel.

The strategy of this cross section ratio measurement will be to require at least one charged lepton passing tight selection criteria in both  $W$  and  $Z^0$  decays to fall in the central, barrel region of the detector, where magnetic tracking analysis augments the calorimeter measurements (see Sec. II). For this measurement, only electrons will be considered.

The number of  $Z^0$ 's limits the statistical accuracy of the  $R$  measurement of  $\Gamma(W)$ , and this tactic of requiring a central electron common to both  $W$  and  $Z^0$  decays decreases the available  $Z^0$  statistics even further. From a simple Monte Carlo simulation (described in Sec. VII), we learn that this requirement is approximately 80% efficient for  $Z^0$ 's. It is only  $\approx 60\%$  efficient for  $W$ 's, but the  $W$ 's do not statistically limit the overall measurement. Requiring a common central electron for both  $W$ 's and  $Z^0$ 's will increase the statistical error on  $R$  from 2.6% to

TABLE I. Previous measurements of  $\Gamma(W)$ .

Experiment	Method	Mode	$\sqrt{s}$ (TeV)	$\Gamma(W)$ (GeV)
CDF [9]	$R$	$e$	1.8	$2.064 \pm 0.085$
CDF [10]	$R$	$e$	1.8	$2.14 \pm 0.20$
CDF [11]	$R$	$\mu$	1.8	$2.21 \pm 0.27$
UA1 [12]	$R$	$\mu$	0.63	$2.19 \pm 0.30$
UA2 [13]	$R$	$e$	0.63	$2.10 \pm 0.16$
UA1 [14]	Direct	$e$	0.63	$2.8 \pm 1.9$
CDF [15]	Direct	$e$	1.8	$2.11 \pm 0.32$

2.9%.

This method of requiring one central electron common to both  $W$  and  $Z^0$  decays, however, decreases the systematic error in the measurement. The selection criteria for the central electron (which appear in the factors  $\epsilon_W$  and  $\epsilon_Z$ ) will almost completely cancel in the ratio  $R$  because they are common to  $W$ 's and  $Z^0$ 's. Imposing tight selection criteria on the central lepton allows loose selection criteria to be applied on the second lepton (either electron or neutrino). The systematic error in the ratio of acceptances is also smaller than for the individual acceptances when a common central electron is required. Furthermore, because of the magnetic analysis in the barrel region of the detector, systematic errors from  $W$  and  $Z^0$  backgrounds are much smaller in the barrel than in the end-cap regions. These smaller uncertainties offset the expected 0.3% increase in statistical error from requiring the common central electron.

#### E. Electrons in $p\bar{p}$ collisions

In addition to presenting a measurement of the  $W/Z^0$  cross section ratio in  $p\bar{p}$  collisions, this paper attempts to describe the other sources of inclusive electrons. Electrons from  $W$  and  $Z^0$  decay account for only a fraction of the high- $P_T$  inclusive electrons observed in our detector, and the study of these other electrons is not only of in-

terest in determining the backgrounds to the  $W/Z^0$  samples, but of interest in its own right. We anticipate that electrons in  $p\bar{p}$  collisions fall into three categories: (1) electrons which come in  $e^+e^-$  pairs, either from photon conversions or Dalitz decays; (2) electrons from heavy quark decay; and (3) hadrons that fake electrons. We discuss techniques to differentiate between these different sources of electrons and their relative contributions to the inclusive electrons observed.

#### F. Outline of paper

The article will proceed as follows. Section II describes electron and neutrino identification in the CDF detector. Section III describes the selection of the inclusive electron sample and the separation of this sample into  $W$  and  $Z^0$  samples and a non- $W/Z^0$  control sample of electrons. Section IV describes the physics sources of high- $P_T$  electrons in the non- $W/Z^0$  sample. This description is used in Sec. V, where we discuss the makeup of the  $W$  sample and estimate the backgrounds. Section VI discusses the  $Z^0$  candidate sample and its backgrounds. Section VII describes the Monte Carlo program used to determine the acceptance ratio  $A_W/A_Z$ . Section VIII describes the efficiencies  $\epsilon_W$  and  $\epsilon_Z$ . Section IX provides a cross-check of the  $R$  measurement, and Sec. X summarizes the extraction of  $\Gamma(W)$  from the cross sections.

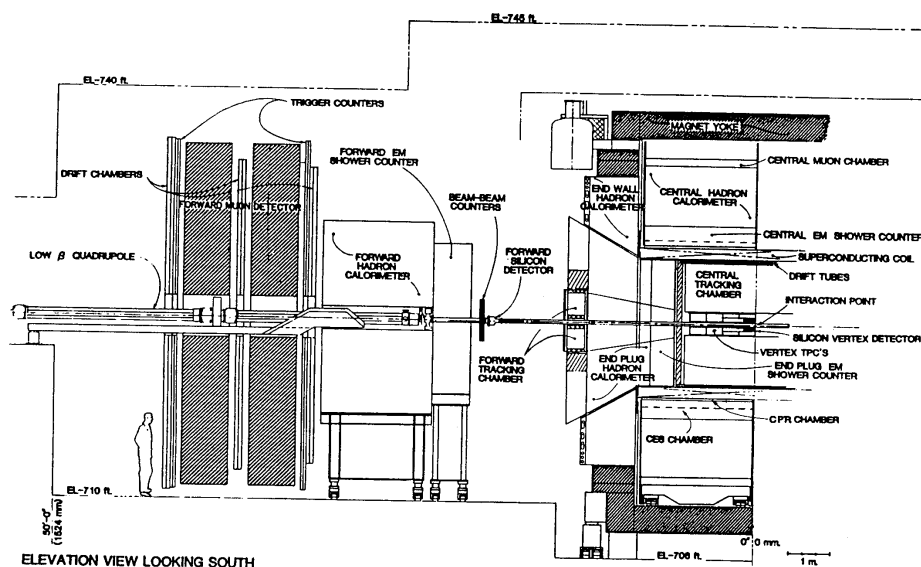


FIG. 1. View of one-half of the CDF Detector.

## II. ELECTRON AND NEUTRINO IDENTIFICATION

Many previous publications [18] give detailed descriptions of the various components of the Collider Detector at Fermilab (CDF) detector. In this section, we summarize briefly the physical characteristics of those detector components relevant for electron and neutrino identification and describe their performance during the 1992-1993 run.

### A. CDF detector

CDF is a cylindrical detector with a central barrel region, two end-cap (plug) regions closing the barrel, and two far-forward detector regions (see Fig. 1). It features electromagnetic (EM) and hadronic (Had) shower counters arranged in projective tower geometry, as well as charged particle tracking chambers. The tracking chambers are immersed in a 1.4 T magnetic field oriented along the proton beam direction provided by a 3 m diam, 5 m long superconducting solenoidal magnet coil. Although not used in this analysis, drift chambers outside the hadron calorimeters for muon detection cover the region  $|\eta| < 1.0$  [19].

#### 1. Calorimeters

Table II summarizes the calorimeter subsystems at CDF. In the central barrel region covering the angular region  $-1.1 < \eta < 1.1$ , the electromagnetic (CEM) and hadron (CHA, WHA) calorimeters are made of absorber sheets interspersed with scintillator. Plastic light guides bring the light up to two phototubes per EM tower. The towers are constructed in 48 wedges, each consisting of 10 towers in  $\eta$  by one tower in  $\phi$  (see Fig. 2). Proportional

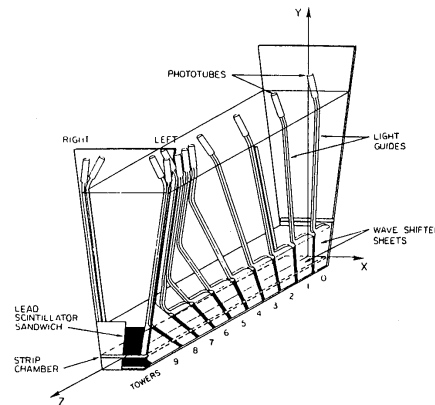


FIG. 2. View of one wedge of the central calorimeters. Each wedge covers 1 tower in the azimuthal direction ( $\Delta\phi = 15^\circ$ ) and 10 towers in the  $\eta$  direction ( $0 < |\eta| < 1.1$ ). One proportional chamber (CES chamber) is embedded at shower maximum in the range  $0 < |\eta| < 0.613$  and another in the range  $0.623 < |\eta| < 1.1$ . Both edges ( $1^\circ$  on either side of the  $15^\circ$  wedge) are uninstrumented in order to leave space for light guides that connect the scintillator to the photomultiplier tubes.

chambers are embedded near shower maximum, 6 radiation lengths ( $X_0$ ) within the EM calorimeters. These chambers, called central electron strip (CES) chambers, have wires in the  $r$ - $\phi$  view and cathode strips in the  $z$  view. The CES is summarized in Table III. A second set of proportional chambers, the central preradiator (CPR), placed in between the front face of the EM calorimeters

TABLE II. Description of the CDF calorimeter subsystems.

	CEM	CHA, WHA	PEM	PHA	FEM	FHA
Energy resolution ( $\%/\sqrt{E}$ )	13.5	80	28	130	25	141
Angular coverage (in $ \eta $ )	$< 1.1$	$< 1.3$	1.1-2.4	1.3-2.4	2.2-4.2	2.3-4.2
Segmentation ( $\Delta\eta \times \Delta\phi$ )	$0.1 \times 15^\circ$	$0.1 \times 15^\circ$	$0.1 \times 5^\circ$	$0.1 \times 5^\circ$	$0.1 \times 5^\circ$	$0.1 \times 5^\circ$
Active medium	lead, scintillator	iron, scintillator	lead, proportional tube	iron, proportional tube	lead, proportional tube	iron, proportional tube
Position resolution ( $r$ - $\phi$ )	0.2 cm	10 cm	0.2 cm	2 cm	0.2 cm	3 cm
$\times z$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$
Longitudinal depth	0.2 cm <sup>a</sup>	5 cm	0.2 cm	2 cm	0.2 cm	3 cm
	18 $X_0$ , <sup>b</sup>	4.7 $\Lambda_{\text{abs}}$	19 $X_0$	5.7 $\Lambda_{\text{abs}}$	25 $X_0$	7.7 $\Lambda_{\text{abs}}$
	1.0 $\Lambda_{\text{abs}}$		1.0 $\Lambda_{\text{abs}}$		0.8 $\Lambda_{\text{abs}}$	

<sup>a</sup>When CES chamber information is used.

<sup>b</sup>Including the 0.9  $X_0$  solenoidal magnet coil.

TABLE III. Description of the shower max detector (CES) and preshower detector (CPR).

	CES chamber		CPR chamber
	Wires ( $r$ - $\phi$ view)	Strips ( $z$ view)	Wires ( $r$ - $\phi$ view)
Number of channels	32	69, <sup>a</sup> 59 <sup>b</sup>	16
Spacing (cm)	1.45	1.67, <sup>a</sup> 2.07 <sup>b</sup>	2.2
Spatial resolution (cm)	0.2	0.2	
Saturation energy (GeV)	150	150	> 150
Chamber length in $z$ (cm)		234	103
Chamber width in $\phi$ (°)		14.0	12.1

<sup>a</sup>For CES segment between 6 cm <  $z$  < 115 cm.<sup>b</sup>For CES segment between 115 cm <  $z$  < 240 cm.

and the magnet coil, act as a shower presampler. Both the CES and CPR are split into two separate readout segments in the  $z$  direction, so that the wires do not run along the full length of the calorimeter, but are read out in two divisions.

In the plug end-cap and forward detector regions, the towers are made of absorber sheets sandwiched with conductive plastic proportional tube arrays. Cathode strips outside the plastic tubes are read out and provide tower segmentation. Near shower maximum in the plug EM (PEM) calorimeter, a layer with finer-spaced strips provides shower profile and precise position determination.

Arrays of scintillator planes are mounted on the front face of each of the far-forward EM shower counters. These planes, called the beam-beam counters (BBC's) are shown in Fig. 1 and are used to signal an inelastic collision. At lower instantaneous luminosities, a coincidence of at least one hit in each plane of the BBC's is required to initiate the trigger system. Each BBC consists of an array of 16 scintillator planes and 16 photomultiplier tubes that encircle the 360° around the beam pipe and cover the pseudorapidity range  $3.24 < |\eta| < 5.90$ . At higher instantaneous luminosities, the mean number of  $p\bar{p}$  interactions per crossing of  $p$  and  $\bar{p}$  bunches is suf-

ficiently high that the BBC coincidence was unnecessary to guarantee the presence of an inelastic collision.

## 2. Charged particle tracking

Within the 1.4 T axial magnetic field of the solenoidal magnet are three detectors for charged particle tracking. The silicon vertex detector (SVX) is a four-layer silicon microvertex detector with single-sided readout to provide precise  $r$ - $\phi$  information for the reconstruction of track impact parameters. The vertex tracking chamber (VTX) is a time projection chamber in 8 modules with a maximum drift distance of 10 cm. It provides reconstruction of the primary event vertex in the  $z$  direction with  $\sigma_z = 1$  mm accuracy. The central tracking chamber (CTC) is a large drift chamber with 84 layers of sense wires organized into 9 superlayers. Four of the superlayers are tilted  $\pm 3^\circ$  with respect to the  $z$  axis so as to provide stereo position measurement of charged particle tracks. The three tracking chambers are summarized in Table IV.

TABLE IV. Description of the charged particle tracking chambers.

	Silicon vertex detector (SVX)	Vertex tracking chamber (VTX)	Central tracking chamber (CTC)
Polar angle coverage	$ \eta  < 1.0$	$ \eta  < 3.25$	$ \eta  < 1.5$
Inner, outer radii (cm)	2.7, 7.9	8, <sup>a</sup> 22	30.9, 132.0
Length (cm)	26	280	320
Layers	4	24	60 axial, 24 stereo
Strip or wire spacing	60 $\mu\text{m}$ (inner 3 lay.) 55 $\mu\text{m}$ (outer layer)	6.3 mm	10 mm
Spatial resolution	15 $\mu\text{m}$ ( $r$ - $\phi$ )	200–500 $\mu\text{m}$ ( $r$ - $z$ )	200 $\mu\text{m}$ ( $r$ - $\phi$ ) 4 mm ( $r$ - $z$ )
Momentum resolution	$\delta P_T/P_T = 0.001 \times P_T^b$		$\delta P_T/P_T = 0.002 \times P_T$
Thickness ( $\theta = 90^\circ$ )	$\approx 0.035 X_0$	$\approx 0.045 X_0$	$\approx 0.015 X_0$

<sup>a</sup>For inner 2 modules. Outer 6 modules are 3 cm inner radius.<sup>b</sup>With both CTC and SVX hits incorporated into track fit.

### B. Electron cluster candidates

Electron identification begins with a clustering algorithm to identify electron showers. An electron cluster consists of a seed tower (the tower in the cluster with the largest energy) and shoulder towers (adjacent towers incorporated into the cluster). Towers with electromagnetic (EM) transverse energy  $E_T > 3$  GeV are eligible to be seed towers [20]. Towers with EM  $E_T > 0.1$  GeV are eligible to be shoulder towers. Beginning with each seed tower, a cluster is formed by incorporating neighboring shoulder towers until either no further adjacent towers may be incorporated or until the maximum cluster size is reached. The maximum cluster size is restricted to three towers in pseudorapidity ( $\Delta\eta \approx 0.3$ ) by one tower in azimuth ( $\Delta\phi \approx 15^\circ$ ) in the central region, five towers in pseudorapidity ( $\Delta\eta \approx 0.5$ ) by five towers in azimuth ( $\Delta\phi \approx 25^\circ$ ) in the plug region, and seven towers in pseudorapidity ( $\Delta\eta \approx 0.6$ ) by seven towers in azimuth ( $\Delta\phi \approx 35^\circ$ ) in the forward region. Finally, it is required that the EM  $E_T$  of the cluster be greater than 5 GeV and that the ratio of hadronic  $E_T$  to electromagnetic  $E_T$  be less than 0.125 [21].

### C. Fiducial volume for electrons

Figure 3 shows schematically the fiducial volume of the detector for electrons used in this analysis. Of the central region defined by  $|\eta| < 1.1$ , 78.9% of the area in  $\eta$ - $\phi$  space is in the fiducial volume for electrons; 78.5% of the region  $|\eta| < 3.6$  is in the fiducial volume for electrons.

In the central region, the electron position is determined using the CES shower position and is required to lie within 21 cm of the tower center in the  $r$ - $\phi$  view so that the shower is fully contained in the active region. The region  $|\eta| < 0.05$ , where the two halves of the de-

tector meet, is excluded. The region  $0.77 < \eta < 1.0$ ,  $75^\circ < \phi < 90^\circ$  (the “chimney”) is uninstrumented because it is the penetration for the cryogenic connections to the solenoidal magnet. In addition, the region  $1.05 < |\eta| < 1.10$  is excluded because of the smaller depth of the electromagnetic calorimeter in this region.

In the plug and forward regions, the electron position is determined from the seed tower (see Sec. II A). The boundaries between detector regions,  $1.1 < |\eta| < 1.2$  and  $2.2 < |\eta| < 2.4$ , are excluded because of the overlap between detectors. The region  $3.6 < |\eta| < 4.2$  in the forward region is excluded. In both the plug and forward calorimeter, the electron seed tower is required not to be adjacent to the quadrant boundaries. This is  $\pm 5^\circ$  around each quadrant boundary.

### D. Central electron identification

Electron identification in the central region is made more powerful by the presence of the central tracking chamber, the central strip chambers, and the central preradiator. Using the electron identification variables described here and the cut values in Table V for tight central electron candidates, the fraction of hadron jets falsely identified as electrons is estimated to be  $2 \times 10^{-5}$  for jets with  $E_T > 20$  GeV (note at CDF that the dominant background to high- $P_T$  electron candidates is not isolated pions, but jets of hadrons). The CPR may be used to further reduce the misidentification rate by one order of magnitude. The purity of electron candidates with  $E_T > 20$  GeV with the cuts of Table V is approximately 84%.

#### 1. Calorimeter transverse profile

The transverse profile, or “ $L_{shr}$ ,” of a central electron allows a comparison of the lateral sharing of energy in the calorimeter towers of an electron cluster to electron shower shapes from test beam data. The variable  $L_{shr}$  is defined as

$$L_{shr} = 0.14 \sum_i \frac{E_i^{adj} - E_i^{prob}}{\sqrt{0.14^2 E + (\Delta E_i^{prob})^2}},$$

TABLE V. Inclusive central electron cuts.

$E_T$	$> 20$ GeV
$L_{shr}$	$0.5 < E/p < 20$
$\chi^2_{strip}$	$< 0.2$
$ \delta x $	$< 10.0$
$ \delta z $	$< 1.5$ cm
$\frac{Had}{EM}$	$< 3.0$ cm
$ Z_{vertex} $	$< 0.045 + 0.055 \left( \frac{E(\text{GeV})}{100} \right)$
Electron triggers the event	

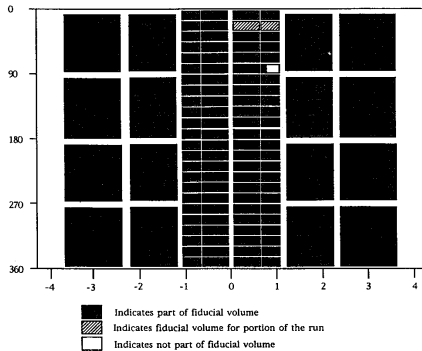


FIG. 3. Map in  $\eta$ - $\phi$  space of fiducial volume for electrons.



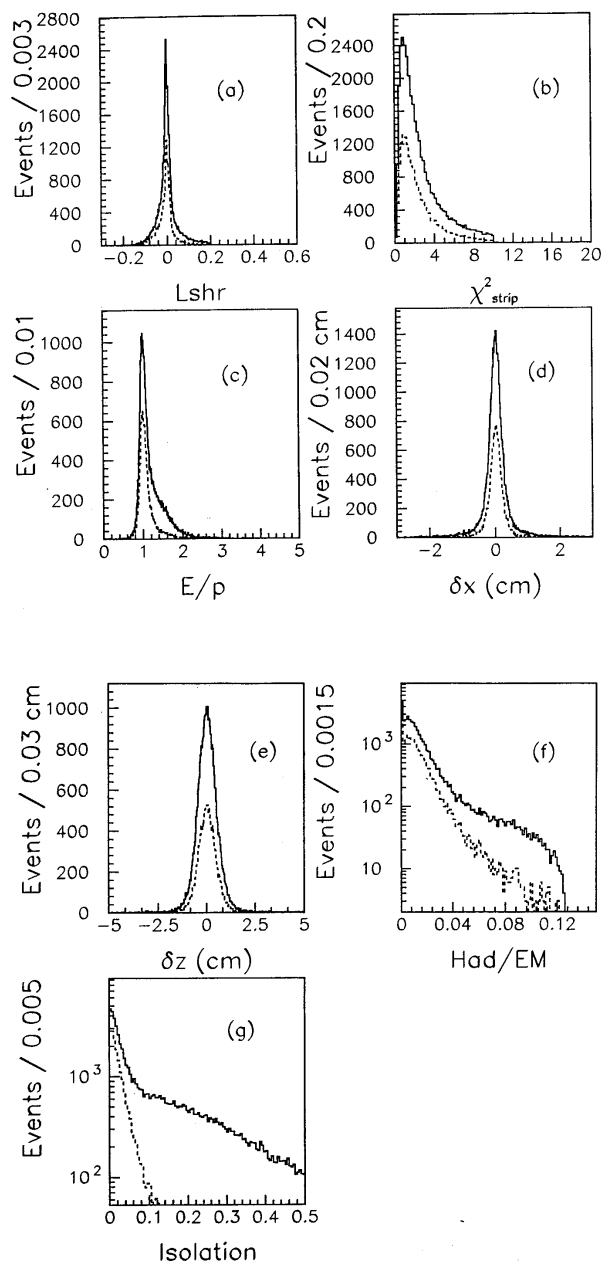


FIG. 4. Central identification variables for inclusive electrons (solid histograms) and electrons from  $W \rightarrow e\nu$  decays (dashed histograms), as described in text.

where  $E_i^{\text{adj}}$  is the measured energy (in GeV) in a tower adjacent to the seed tower,  $E_i^{\text{prob}}$  is the expected energy (in GeV) in the adjacent tower,  $0.14\sqrt{E}$  (in GeV) is the error on the energy measurement, and  $\Delta E_i^{\text{prob}}$  (in GeV) is the error on the energy estimate.  $E_i^{\text{prob}}$  is calculated using a parametrization from test beam data. The distribution of  $L_{\text{shr}}$  for inclusive and  $W$  electrons is shown in Fig. 4(a).

## 2. Strip chamber pulse height

The CES chamber, embedded 6 radiation lengths into the central electromagnetic calorimeter, can be used to observe the longitudinal development of a shower. An electromagnetic shower in the calorimeters is generally initiated much earlier for an electron than for a hadron. Shown in Fig. 5(a) is the variable  $\text{CES}/p \equiv (\sum Q_i)/p$  for electrons and hadrons, where  $Q_i$  is the charge on a strip [in analog-to-digital converter (ADC) counts],  $p$  is the track's momentum (in GeV/c), and the sum is over the 5 strips ( $z$  view) around the track's position extrapolated to the strip chambers.

## 3. Strip chamber pulse height shape

The pulse height shape in the CES is also used for electron identification. The pulse height shape is compared to test beam data using a  $\chi^2$  test. The variable  $\chi_{\text{strip}}^2$  is the  $\chi^2$  of the fit of the energy deposited on each of the 11 strips in  $z$  in the CES shower compared to the test beam shape. A similar variable  $\chi_{\text{wire}}^2$  tests the energy deposition on the wires in the  $r$ - $\phi$  view. The variable  $\chi_{\text{strip}}^2$  for inclusive electron candidates and for electrons from  $W$  decays is shown in Fig. 4(b).

## 4. Charged track requirement

Electromagnetic clusters in the calorimeters can arise from neutral particles, such as  $\pi^0 \rightarrow \gamma\gamma$  decay. We require the presence of a charged track in the CTC for

electron identification. We require the ratio of the electromagnetic energy,  $E$ , of the electron cluster measured in the calorimeter to the electron's momentum,  $p$ , measured in the central tracking chamber to lie in the range  $0.5 < E/p < 2.0$ . The distribution of the variable  $E/p$  for inclusive electron candidates and for electrons from  $W$  decays is shown in Fig. 4(c). The tail above  $E/p > 1$  in  $W$  electrons is due to the radiation of photons by the electron as they pass through the material inside the CTC. The radiated photons generally land in the same calorimeter cell as the electron, so  $E$  has the same value as the initial electron energy, but  $p$  is smaller as it is measured in the CTC after the Bremsstrahlung radiation. This tail is larger in the inclusive electrons because of the presence of electrons from  $\pi^0 \rightarrow \gamma\gamma \rightarrow \gamma e^+ e^-$ , for which  $p$  is the momentum of one electron, but  $E$  is close to the energy of the pion.

## 5. Track-shower matching variables

The CTC track pointing to the electron cluster is extrapolated to the CES, and the extrapolated position is compared to the shower position as measured in the CES. The variable  $\delta x$  is the separation in the  $r$ - $\phi$  view between the extrapolated track position and the CES strip cluster position. The variable  $\delta z$  is the corresponding separation in the  $z$  view. Cutting on these variables reduces the background from overlaps of charged and neutral hadrons. The variables  $\delta x$  and  $\delta z$  for inclusive electron candidates and for electrons from  $W$  decays are shown in Fig. 4(d,e).

## 6. CPR pulse height

The CPR pulse height on the two wires around a track is used to discriminate electrons from hadrons. An electron may begin to shower in the solenoid, while a hadron will leave only a minimum-ionizing pulse. The solenoidal coil thickness is  $0.85 X_0$  at normal incidence. Figure 5(b) shows the pulse height shapes for electrons and hadrons.

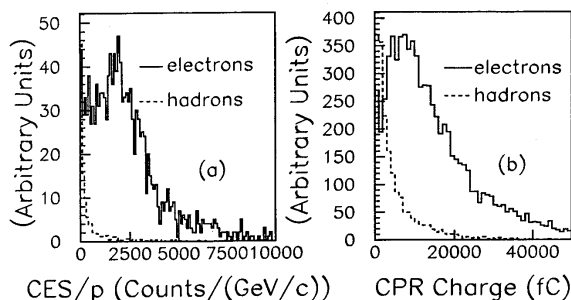


FIG. 5. (a) Strip chamber (CES) pulse height for electrons and hadrons; (b) CPR pulse height for electrons and hadrons. The relative normalizations between the two shapes is arbitrary.

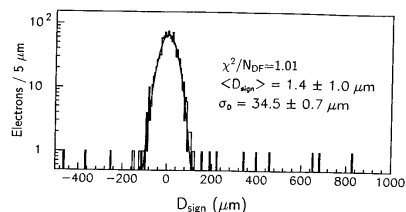


FIG. 6. Signed impact parameter for electrons from  $Z^0 \rightarrow e^+e^-$  decays observed in the SVX detector.

#### 7. Electron track impact parameter

The impact parameter of the electron's track is used to discriminate electrons of long-lived parent particles from those originating from primary vertex of the  $p\bar{p}$  collision. The lifetime of bottom quarks is  $c\tau \sim 400 \mu\text{m}$ , while the impact parameter,  $d_0$ , resolution is  $\sigma_d \sim 40 \mu\text{m}$ . The lifetime of the  $W$  and  $Z^0$  are negligible on this scale. For charged tracks with  $P_T > 1 \text{ GeV}/c$ , the dominant contribution to the impact parameter resolution is the uncertainty in the primary vertex position.

The "signed impact parameter"  $D_{\text{sign}}$  is defined for a track in the CTC pointing to a jet in the calorimeters. It is defined as

$$D_{\text{sign}} = d_0 \left( \frac{\vec{d}_0 \cdot \hat{n}_{\text{jet}}}{|\vec{d}_0 \cdot \hat{n}_{\text{jet}}|} \right),$$

where  $\vec{d}_0$  is the vector which points from the primary vertex to the point of closest approach of the track to the primary vertex. The unit vector  $\hat{n}_{\text{jet}}$  points from the primary vertex to the energy centroid of the jet in the calorimeter. A track emanating from the decay vertex of a long-lived parent will have positive  $D_{\text{sign}}$ , whereas a track from the primary vertex will have, on average, zero  $D_{\text{sign}}$ .

The resolution effects which smear the observed  $D_{\text{sign}}$  spectrum are the position resolution of the individual hits in the SVX layers, scattering of the electron in the beampipe before reaching the SVX, radiation of photons by the electron as it passes through the material in the tracking volume, and the location uncertainty of the primary vertex. The  $D_{\text{sign}}$  distribution for electrons from  $Z^0 \rightarrow e^+e^-$  decays is shown in Fig. 6. The observed  $\sigma$  agrees well with the dominant contributions of the  $\sigma = 32.5 \mu\text{m}$  effect of the primary vertex spread (see Fig. 7), and the  $\sigma = 10.7 \mu\text{m}$  effect of Bremsstrahlung radiation (estimated from a Monte Carlo simulation). The impact parameter significance,  $D/\sigma \equiv D_{\text{sign}}/\sigma$  is shown for electrons from  $Z^0 \rightarrow e^+e^-$  decays in Fig. 8(a). Figure 8(b) shows that the events in the tails are, in fact,  $Z^0$ 's and not background. The non-Gaussian  $D/\sigma$  tails come from accidental hits in the SVX incorrectly incorporated into the track fit.

#### 8. Event vertex measurement

The position in  $z$  of the primary event vertex is measured by the vertex tracking chamber (VTX). The  $z$  position of the event is distributed about the nominal interaction point by  $\sigma = 26 \text{ cm}$  (see Fig. 9). This spread is an average of many different  $\sigma$ 's from different physics runs. The spread of the interaction point in  $z$  has implications for use of the SVX in physics analyses, since it is larger than the length of the SVX. From studying the tracks from  $Z^0$  decays,  $61.9 \pm 1.3\%$  of primary vertices are contained within the SVX.

#### 9. Leakage into the hadronic calorimeters

The ratio Had/EM of the energy in the hadronic towers of the electron cluster (Had) to the energy in the electromagnetic towers in the electron cluster (EM) is used to further select good electrons. The electromagnetic calorimeters nearly contain electromagnetic showers, while hadron showers in general deposit energy in both the hadronic and electromagnetic compart-

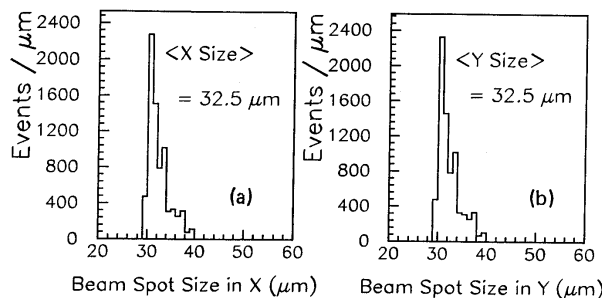


FIG. 7. Size in (a) the  $x$  and (b) the  $y$  view of the overlapping region of proton and antiproton beams for several physics runs (proton stores).

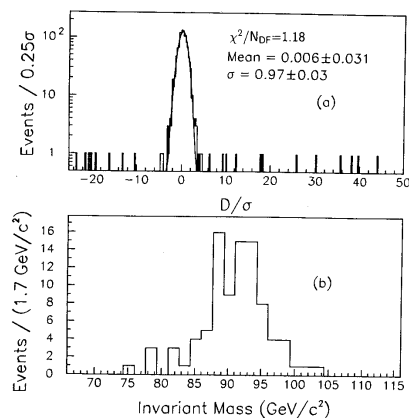


FIG. 8. (a) The normalized impact parameter distribution  $D/\sigma$  for electrons from  $Z^0 \rightarrow e^+e^-$  decays. The  $\sigma$  agrees well with the sum of the estimated effects of beam spot size and multiple scattering; (b) invariant mass for  $Z^0$ 's with  $|D/\sigma| > 2$ .

ments. This quantity is physics dependent, however, since isolated electrons have less hadronic energy nearby than would electrons produced in association with hadrons (such as electrons from semileptonic  $b$  decay, which in general are associated with a jet of hadrons from the decay of the charmed meson). The distribution of Had/EM for inclusive and  $W$  electrons is shown in Fig. 4(f). As expected, the  $W$  electrons and the inclusive electrons have a different Had/EM shape.

#### 10. Calorimeter isolation

This cut is not an electron identification cut but a topology cut. Electrons from  $W$  and  $Z^0$  decay are expected to be "isolated." That is, they are not expected to

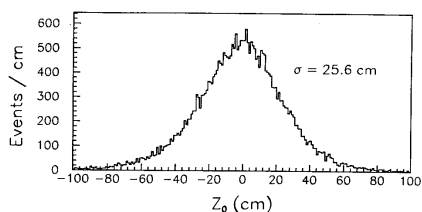


FIG. 9. The distribution,  $Z_0$ , of the position in  $z$  of event vertex for inclusive electron events.

be produced in association with other particles. As mentioned above, electrons from other physics processes are produced associated with jets of other particles nearby in  $\eta$ - $\phi$  space. We use the "isolation" variable  $I$  in order to select electrons not associated with other hadronic activity. The  $I$  variable is defined as

$$I = \frac{E_T^{\text{cone}} - E_T^{\text{cluster}}}{E_T^{\text{cluster}}},$$

where  $E_T^{\text{cone}}$  is the sum of the EM and Had transverse energies in all of the towers (including the electron cluster) in a radius of  $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$  centered around the electron cluster, and  $E_T^{\text{cluster}}$  is the electromagnetic transverse energy in the electron cluster. The variable  $I$  for inclusive electron candidates and for electrons from  $W$  decays is shown in Fig. 4(g). Again, the shapes are different, the inclusive electrons being less isolated.

#### E. Plug electron identification

The track-finding efficiency for tracks in the central tracking chamber falls rapidly in the range of  $\eta$  covered by the plug calorimeters. Consequently, information from the CTC in the region covered by the plug calorimeters is not used in this analysis. To identify the presence of charged tracks pointing toward the cluster, the occupancy in the vertexing chamber (VTX) octant pointing toward the electron cluster is used (see Fig. 10). This variable is the ratio of layers in the VTX on which the electron deposits charge divided by the expected number of layers in the VTX to be traversed by the electron, given the electron's trajectory. The ratio Had/EM is used, as is the isolation variable  $I$ . The variable  $\chi_{3 \times 3}^2$  is used. This variable is a fit of the lateral sharing of energy in the 3 towers in  $\eta$  by the 3 towers in  $\phi$  around the electron cluster's center to the shape expected from test beam data. The distribution of these variables for  $Z^0 \rightarrow e^+e^-$  events with a central electron and a plug electron are shown in Fig. 10.

#### F. Forward electron identification

Electrons in the regions covered by the forward calorimeters are identified solely by the Had/EM,  $I$ , and VTX occupancy variables. No other tracking or lateral sharing variables are used. The distributions of these variables for  $Z^0 \rightarrow e^+e^-$  events with a central electron and a forward electron are shown in Fig. 11.

#### G. Central electron trigger

A three-level multipurpose trigger [22] is used to select  $p\bar{p}$  events for analysis. The first two levels are programmable hardware triggers, while level 3 is a software trigger. This section describes the trigger selection for central electrons.

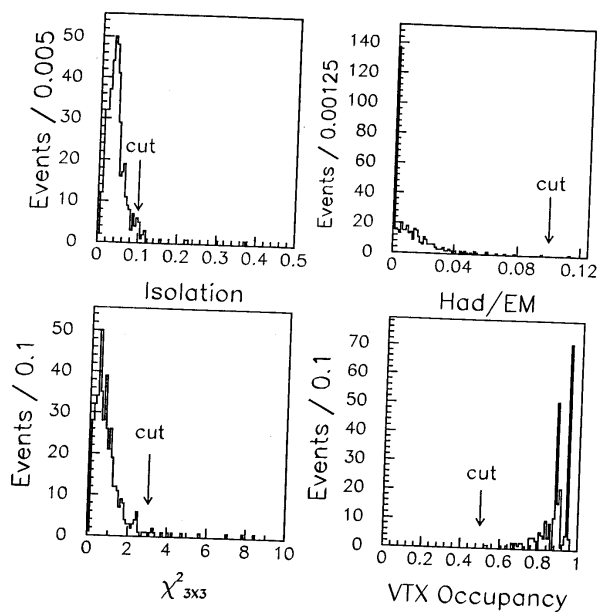


FIG. 10. Plug electron identification variables (see text) for events with one electron in the central region and a second cluster in the plug for which the pair has an invariant mass within the 81–101  $\text{GeV}/c^2$  mass range.

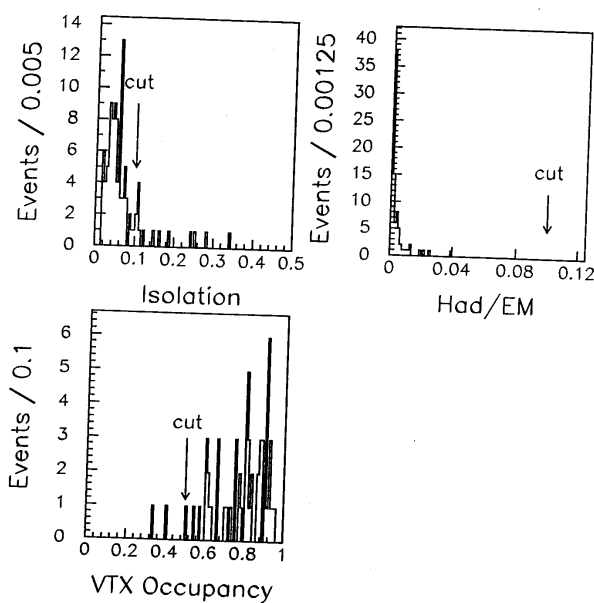


FIG. 11. Forward electron identification (see text) variables for events in which one electron is in the central region and a second cluster in the forward for which the pair has an invariant mass within the 81–101  $\text{GeV}/c^2$  mass range.

In the level 1 trigger, energies in physical calorimeter towers of  $0.1 \times 15^\circ$  in  $\eta$ - $\phi$  space are first summed into  $0.2 \times 15^\circ$  trigger towers. One trigger tower is required to satisfy  $E_T > 7$  GeV. A coincidence of hits in the two BBC's is also required. As shown in Fig. 12, the efficiency of this trigger for fiducial electrons is  $99.2 \pm 0.1\%$  for electrons with  $E_T > 10$  GeV.

Level 2 performs a cluster search and matches clusters to CTC tracks. EM trigger towers with  $E_T > 9$  GeV are cluster seeds. Adjacent EM towers are then added to the cluster if they have  $E_T > 7$  GeV. A cut of  $(EM+Had)/EM < 1.125$  is imposed on electron candidate clusters. A hardware track processor [23] ("central fast tracker," or CFT) searches for tracks in the  $r$ - $\phi$  plane in the CTC. For the electron trigger, a track of  $P_T > 9.2$  GeV/c is required to point to the electromagnetic cluster. As shown in Fig. 12, the level 2 efficiency is flat vs  $E_T$  in the region of our concern (the threshold is at 9 GeV). The inefficiency of this trigger for  $W$  and  $Z^0$  electrons is dominated by the CFT track reconstruction. This efficiency decreases at large  $|\eta|$ , as shown in Fig. 13. The overall efficiency of this trigger for  $W$  and  $Z^0$  electrons in the fiducial volume was  $91.5 \pm 0.3\%$  for this run.

In the level 3 electron trigger, an electron cluster is required with  $E_T > 18$  GeV. A three-dimensional track with  $P_T > 13$  GeV/c is required to point to the electron cluster. The cuts  $L_{shr} < 0.1$ ,  $|\delta x| < 3$  cm, and  $|\delta z| < 5$  cm are imposed. For this run, the average level 3 trigger efficiency for electrons in the fiducial volume is  $98.2 \pm 0.1\%$ .

In addition to the electron triggers described above, a set of backup triggers were implemented which select  $W \rightarrow e\nu$  events based not on the electron, but on the

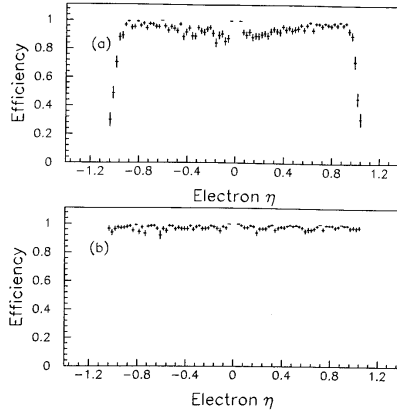


FIG. 13. Efficiency of the electron trigger vs  $\eta$  (a) in level 2 and (b) in level 3. The measurement of the electron trigger efficiency is described in Sec. VIII E.

neutrino, or  $\cancel{E}_T$  (see Sec. II H). These backup triggers require the presence of a neutrino, or  $\cancel{E}_T$ , greater than 25 GeV, and either a calorimeter cluster or a high- $P_T$  track. These triggers are used to study the efficiency of the electron identification cuts in the trigger.

#### H. Neutrino identification

The calorimeter response to the total activity in the event determines the resolution on the measurement of

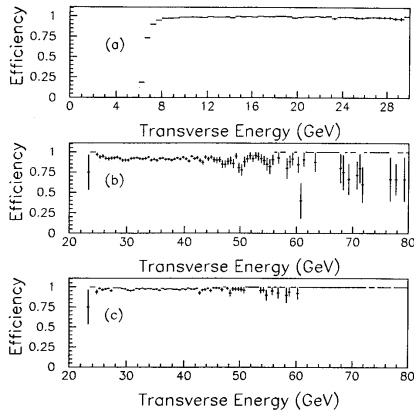


FIG. 12. Electron trigger efficiency in (a) level 1, (b) level 2, and (c) level 3 vs the electron  $E_T$ . The measurement of the electron trigger efficiency is described in Sec. VIII E.

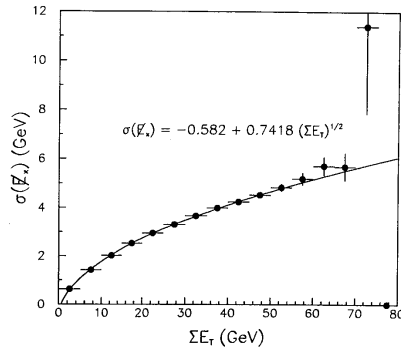


FIG. 14. Fitted  $\sigma(\cancel{E}_T)$  vs  $\Sigma(E_T)$  in minimum bias trigger events. The curve is a best fit of a square root function to the data. The curve does not pass through the origin because run-by-run offsets and out-of-time accidental energy were not corrected for.

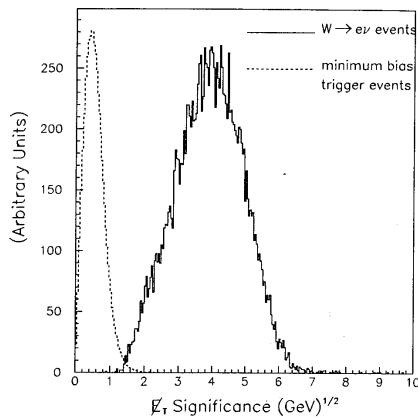


FIG. 15. The missing  $E_T$  significance for the  $W$  candidate events and for a sample of minimum-bias-triggered events.

neutrino  $P_T$ , which is inferred by invoking momentum conservation. A noninteracting neutrino in our detector is detected by the presence of a large transverse momentum imbalance ("missing  $E_T$ ," or  $\cancel{E}_T$ ). The missing  $E_T$  is calculated from

$$\cancel{E}_T \equiv \left| (-1) \times \sum \vec{E}_T^i \right|,$$

where  $\vec{E}_T^i$  is a vector whose magnitude is the transverse energy in a calorimeter tower and whose direction points from the event vertex to the center of the calorimeter tower. The sum is performed within the region  $|\eta| < 3.6$ .

Events with perfect momentum balance and no resolution effects would have  $\cancel{E}_T = 0$ . The smearing about 0 on each component ( $x$  and  $y$ ) of  $\cancel{E}_T$  is Gaussian and grows with the  $\sum E_T$  in the calorimeter, as is shown in the minimum bias trigger sample of Fig. 14. Minimum bias triggers require only a coincidence of hits in both the forward and backward BBC's to signal the presence of an inelastic event. No requirements of the calorimeters are made. The  $\sum E_T$  is the scalar sum of  $E_T$  over all towers in the calorimeter with  $|\eta| < 3.6$ . At the  $\sum E_T$  typical of  $W$  events, the resolution on  $\cancel{E}_T$  is on the order of 3 GeV, while the neutrino  $P_T$  is of order 20–40 GeV. The  $\cancel{E}_T$  significance,  $S \equiv \cancel{E}_T / \sqrt{\sum E_T}$ , is a measure of how many standard deviations away from zero is the  $\cancel{E}_T$  in a particular event. Figure 15 shows  $S$  for minimum bias events and for the  $W$  candidate events in our sample.

### III. INCLUSIVE ELECTRON SAMPLE

Inclusive high- $P_T$  electrons are produced in decays of the electroweak bosons, such as  $W \rightarrow e\nu$ ,  $Z^0 \rightarrow e^+e^-$ ,

or  $Z^0 \rightarrow \tau^+\tau^-$  and  $W \rightarrow \tau\nu$ , where one of the  $\tau$ 's decays to an electron. High- $P_T$  electrons are also produced in QCD processes, where the electron is embedded in a high- $P_T$  jet of hadrons. The processes that can produce an electron cluster in hadronic jets are (1) electrons which come in  $e^+e^-$  pairs, either from photon conversion or Dalitz decays, (2) semileptonic decays of heavy quarks,  $b \rightarrow ce\nu$  or  $c \rightarrow se\nu$ , and (3) hadron showers ("fakes") that pass our electron identification cuts. The hadrons which pass our electron identification cuts are predominantly overlaps of  $\pi^\pm$  and  $\pi^0$  showers and pion charge exchange,  $\pi^\pm + N \rightarrow \pi^0 + N$ , which can occur in the calorimeters. This section describes the selection of a sample of inclusive electrons and of three subsamples: a sample of electrons from  $W$  decays, a sample from  $Z^0$  decays, and a sample of non- $W/Z^0$  electrons. The non- $W/Z^0$  sample is used as a control sample to study the  $W$  backgrounds from hadron jets. Sections IV, V, and VI will describe these samples further and discuss the cross contamination between them.

Candidate events for  $W \rightarrow e\nu$  and  $Z^0 \rightarrow e^+e^-$  decays are selected from a common sample of inclusive high- $P_T$  electrons located in the central detector region which pass tight cuts. Requiring tight cuts on the central electron in  $W$  and  $Z^0$  decay serves three purposes. First, the well-understood central region has added information from the tracking and the strip chambers that can be used to suppress backgrounds from other physics processes. Second, the tight cuts on the central electron allow us to place loose, highly efficient cuts on the second lepton (the neutrino in the case of  $W$  decays and the second electron in the case of  $Z^0$  decays). Third, and perhaps most importantly, selecting both  $W$  and  $Z^0$  candidate events from a common sample of inclusive electrons cancels several systematic uncertainties in the ratio of the  $W$  and  $Z^0$  cross sections.

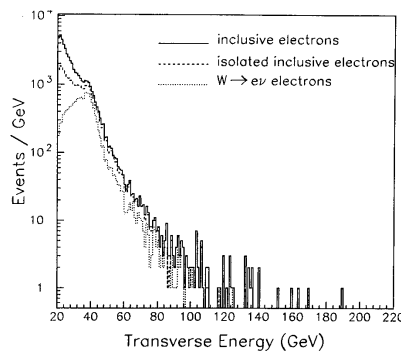


FIG. 16. The  $E_T$  distribution of inclusive electrons, isolated inclusive electrons, and electrons from  $W \rightarrow e\nu$  decays.

TABLE VI.  $Z^0$  selection cuts.

One tight, isolated central electron		
Second electron passing loose cuts:		
Central:	Plug:	Forward:
$E_T > 20$ GeV	$E_T > 15$ GeV	
Had/EM < 0.1	Had/EM < 0.1	$E_T > 10$ GeV
$I < 0.1$	$I < 0.1$	Had/EM < 0.1
Opposite sign charged track	$\chi^2_{3 \times 3} < 3.0$	$I < 0.1$
$E/p < 2.0$		
$66 \text{ GeV}/c^2 < M_{(ee)} < 116 \text{ GeV}/c^2$		

## A. Central electron selection

The selection criteria for a high- $P_T$ , central, tight electron are listed in Table V. In addition, we define a tight, isolated central electron as one which passes the cuts listed in Table V and also has  $I < 0.1$  (see Sec. IID 10).  $I$  is not an identification variable, but an event topology cut.  $W$  and  $Z^0$  electrons are expected to be isolated, but electrons from other physics processes may not be. A total of 50 861 events pass the tight electron event selection criteria in an exposure of  $19.6 \text{ pb}^{-1}$ . A total of 30 349 of these electrons pass the tight, isolated electron event cuts. The  $E_T$  spectra of the tight electrons and the isolated tight electrons are shown in Fig. 16. A peak at 40 GeV from  $W$  and  $Z^0$  decays is already apparent.

B.  $Z^0$  sample selection

$Z^0$  candidates are selected from the inclusive electron sample by requiring that the tight central electron be isolated and also requiring a second isolated electron which passes loose selection criteria. The loose cuts on the second electron are listed in Table VI.

Figure 17 shows the invariant mass distribution of electron pair candidates before and after the cuts of Table VI are imposed. The electron pairs before the cuts of Table VI are imposed consist of one tight isolated central electron (Table V) and a second cluster as defined in Sec. IIB. The dominant background suppression comes from the kinematic cuts on the second electron. We ob-

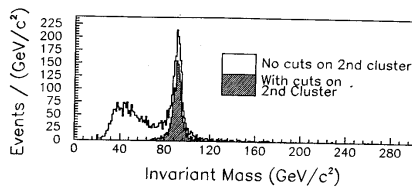


FIG. 17. Invariant mass spectrum of  $e^+e^-$  pairs with one tight central electron and a second cluster, with and without the cuts of Table VI imposed on the second cluster.

serve 1312 events which fall in the  $66\text{--}116 \text{ GeV}/c^2$  mass range. Figure 18 shows the distribution in  $\eta$  of the second lepton of the 1312  $Z^0$  candidates. Table VII shows that the distribution in  $\eta$  of the second lepton corresponds well to expectations from the Monte Carlo program when the different total detector efficiencies and backgrounds are taken into account. The Monte Carlo program is normalized to the  $Z^0$  signal.

C.  $W$  sample selection

To select  $W$ 's from the inclusive electron sample, we (a) require a tight, isolated central electron in the event, (b) require  $E_T > 20$  GeV, and (c) reject  $Z^0$  decays by asking that the event does not possess a second, isolated, electromagnetic cluster which forms a mass with the first electron in the  $66\text{--}116 \text{ GeV}/c^2$  range. Figure 19 shows the  $I$  of the electron in the event vs the  $E_T$  in the event. The  $W$ 's appear as a cluster at low  $I$ , high  $E_T$ . The  $E_T$  spectrum of the isolated ( $I < 0.1$ ) and nonisolated ( $I > 0.3$ ) tight inclusive electrons is shown in Fig. 20. A total of 13 796 events have  $E_T > 20$  GeV and pass our  $Z^0$  rejection cuts. Figure 21 shows the distribution in  $\eta$  of the electrons from the  $W$  candidates. The  $Z^0$  removal cut removes only 41 events, because the missing  $E_T$  requirement strongly suppresses the  $Z^0$ 's.

D. Non- $W/Z^0$  electron sample selection

The  $W$  and  $Z^0$  samples selected above are contaminated by electrons from other physics processes. The

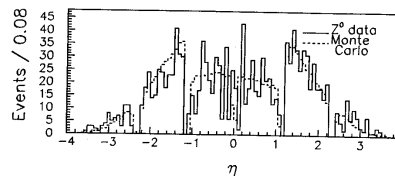


FIG. 18. Distribution in  $\eta$  for  $Z^0 \rightarrow e^+e^-$  decays for the data and the Monte Carlo described in Sec. VII.



TABLE VII.  $Z^0$  yield in different detector regions.

Detector in which 2nd lepton falls	$Z^0$ candidate yield	$Z^0$ background (see Sec. VI)	$Z^0$ signal (yield-background)	Monte Carlo expectation (see Sec. VII)
Central	529	$1 \pm 1$	$528 \pm 23$	$535 \pm 13$
Plug	640	$14 \pm 14$	$626 \pm 29$	$618 \pm 13$
Forward	143	$6 \pm 3$	$137 \pm 12$	$138 \pm 8$

backgrounds of electrons from hadron jets are particularly important to understand. This section describes the selection of a control sample of those electrons from hadron jets. In Sec. IV we examine the makeup of this sample and determine the fractions  $f_{conv}$ ,  $f_b$ , and  $f_{fake}$  of electrons in jets that come from conversions, heavy quarks, and fake electron clusters. The techniques used in Sec. IV are then employed in Sec. V to determine the contamination of the  $E_T > 20$  GeV sample ( $W$  sample) from these hadronic processes.

From the inclusive electron sample of 50 861 events, events which have a second cluster which passes cuts of  $Had/EM < 0.1$  and  $I < 0.1$  are removed in order to reject electrons from  $Z^0 \rightarrow e^+e^-$  and Drell-Yan pair production. Approximately 4600 events are removed by this cut. Events which have  $E_T > 10$  GeV are rejected in order to remove electrons from  $W \rightarrow e\nu$  or  $W \rightarrow \tau\nu \rightarrow e\nu\nu$ . 21 637 events survive this cut. The contamination of this sample from  $W \rightarrow e\nu$ ,  $Z^0 \rightarrow e^+e^-$ ,  $W \rightarrow \tau\nu$ , or  $Z^0 \rightarrow \tau^+\tau^-$  is estimated [24] to be  $1.0 \pm 0.2\%$ . Finally, we require a hadronic jet with  $E_T > 10$  GeV and electromagnetic fraction less than 0.8, which reduces the fraction of electrons from weak boson decays to  $0.4 \pm 0.1\%$  of the sample. The 17 805 electrons passing all of these cuts are used as our control sample of non- $W/Z^0$  electrons.

#### IV. NON- $W/Z^0$ ELECTRON SAMPLE

Electrons from  $W$  and  $Z^0$  decay account for only a fraction of the high- $P_T$  inclusive electrons observed in our detector. In this section we investigate the sources of high- $P_T$  electrons from QCD processes that create electrons embedded in hadron jets. This discussion will be of particular use in Sec. V, in which we discuss the backgrounds to the  $W$  candidates. As mentioned in Sec. III, we anticipate that electrons in hadron jets fall into three categories: (1) electrons which come in  $e^+e^-$  pairs, either from photon conversions or Dalitz decays, (2) electrons from heavy quark decay, and (3) hadrons that fake electrons. Hereafter, electron pairs from photon conversions and from Dalitz decays will be referred to collectively as "conversions."

In this section we use the 17 805 electrons in the non- $W/Z^0$  electron sample to estimate the fraction  $f_{conv}$  of electrons in hadron jets that originate from photon conversions. We also estimate the fraction  $f_b$  of non- $W/Z^0$  electrons from heavy quark decay, and the fraction  $f_{fake}$  of non- $W/Z^0$  electrons that are not electrons but clusters of hadrons. Finally, we estimate how many electrons in the inclusive electron sample (see Sec. III A) come from these three QCD processes.

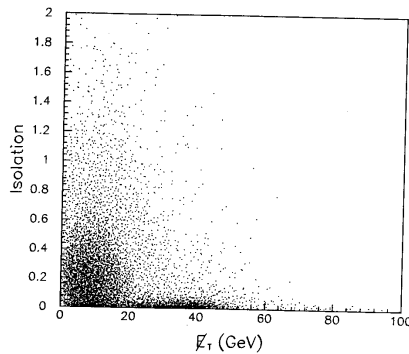


FIG. 19. Isolation of the electron vs the  $E_T$  in the event. Events with a second electromagnetic cluster have been explicitly removed from this plot.

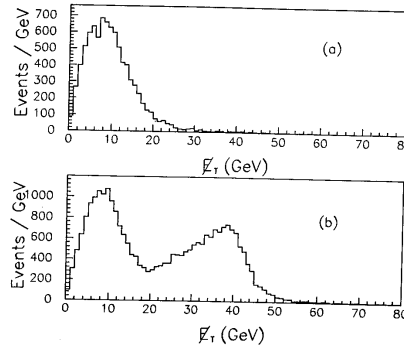


FIG. 20.  $E_T$  spectrum of inclusive electrons with (a)  $I > 0.3$ ; (b)  $I < 0.1$ . The peak at approximately 8 GeV is due to resolution effects and the peak at 40 GeV is due to neutrinos from  $W$  decays. Events with a second electromagnetic cluster have been explicitly removed from these plots.

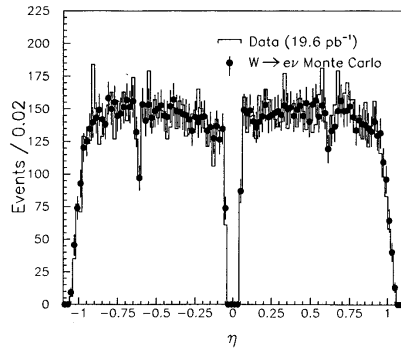


FIG. 21. Distribution in  $\eta$  of electrons from  $W \rightarrow e\nu$  decays.

#### A. Estimate of the conversion electron fraction

Electrons from photon conversions are identified by searching for a second, oppositely signed charged track near the electron track which extrapolates to a common tangent point. We flag as conversions the electrons which have a second track nearby in the CTC passing the following cuts:  $|\delta(r - \phi)| < 0.2$  cm;  $|\delta(\cot\theta)| < 0.06$ . The first cut is on the separation in the  $r$ - $\phi$  view [19] between the two tracks at their tangent point. This variable is given a positive sign if the two circles of the tracks in the  $r$ - $\phi$  view do not overlap, and a negative sign otherwise. The second cut is on the difference in  $\cot\theta$  between the two tracks [19]. Figure 22 shows these variables for track pair candidates in the non- $W/Z^0$  electron sample.

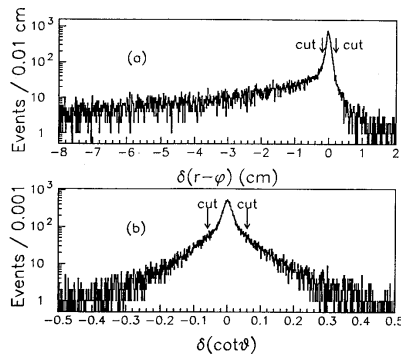


FIG. 22. Distributions in the variables for track pairs used to identify photon conversions: (a)  $\delta(r - \phi)$ ; (b)  $\delta(\cot\theta)$ .

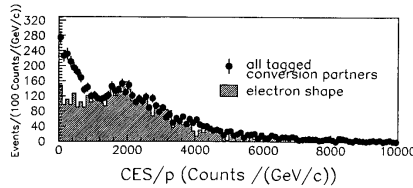


FIG. 23. CES pulse height for partner tracks tagged as conversion pairs and the expected shape for real electrons. Note the excess of track partners at low pulse height beyond that expected for real electrons, indicating the presence of minimum-ionizing hadrons in the conversion pair sample.

Some hadron tracks are falsely flagged as conversion partners by the  $\delta(r - \phi)$  and  $\delta(\cot\theta)$  cuts. In Fig. 23 we show the pulse height left in the CES by the partner track to the electron track for those pairs in Fig. 22 which pass the  $\delta(\cot\theta)$  and  $\delta(r - \phi)$  cuts. Also shown is the expected shape for electrons, which is derived from a pure sample of conversion pairs which was selected based on having a conversion radius consistent with the outer wall of the VTX, at  $r \sim 27$  cm. We estimate that  $89 \pm 2\%$  of the track pairs selected with the  $\delta(\cot\theta)$  and  $\delta(r - \phi)$  cuts are truly conversion pairs. Correcting for the backgrounds and the conversion finding efficiency, we find that  $f_{\text{conv}} = 41.5 \pm 2.2\%$  is the fraction of the non- $W/Z^0$  electron sample that are conversion pairs or Dalitz decays. The conversion-finding efficiency has two components: the efficiency to find the partner track, and the efficiency for the track pair, if found, to pass the  $\delta(\cot\theta)$  and  $\delta(r - \phi)$  cuts. Both of these efficiencies are estimated with a sample of conversions that occur at  $r \sim 27$  cm from the beamline [16].

#### B. Estimate of the $b$ electron fraction

One signature characteristic of a  $b$  quark is its long lifetime. Using the impact parameter significance  $D/\sigma$  of electrons in the silicon vertex detector (SVX), an estimate is made of the number of electrons in the non- $W/Z^0$  sample from  $b$  decay. The impact parameter significance distribution of all electrons in the non- $W/Z^0$  sample is fit to a sum of shapes from  $b$ 's, conversions, and fake electrons. In this fit, the conversion fraction is set to  $f_{\text{conv}} = 41.5\%$  from Sec. IV A, so that the  $b$  and fake fractions are determined. The impact parameter shape for fake electrons is assumed to be the same as that of  $Z^0$  electrons, since they are presumably from light quark jets and have zero lifetime. The impact parameter distribution for the conversions is derived from the conversion sample of Sec. IV A, with the additional requirement that the partner track leave at least 2000 counts/(GeV/c) in the CES (see Fig. 23). The additional requirement on the pulse height is used to obtain a more pure conversion sample.

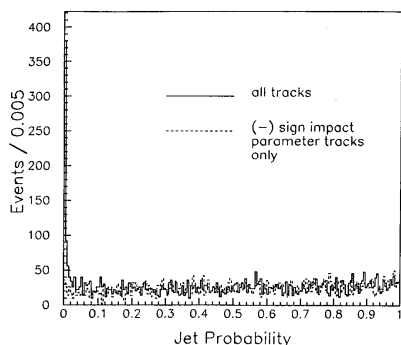


FIG. 24. Probability that the jet comes from the primary vertex for jets in inclusive electron events with  $E_T < 10$  GeV. The distributions are shown for jets in which all tracks or only negatively signed impact parameter tracks are incorporated into the jet probability. The negatives' jet probability shape is indicative of the resolution, and, hence, the shape for light quark jets.

In order to obtain the  $D/\sigma$  shape for  $b$  electrons, we exploit the fact that  $b$ 's in  $p\bar{p}$  collisions are produced in  $b\bar{b}$  pairs, so that we select a data sample of semileptonically decaying  $b(\bar{b})$  quarks by tagging the  $\bar{b}(b)$  jet in the event with a  $b$ -tagging algorithm [25]. Selecting  $b$  events using only the away jet to identify the  $b$  electron applies negligible bias to the signed impact parameter distribution for  $b$  electrons.

In the  $b$ -tagging algorithm, a probability is formed per

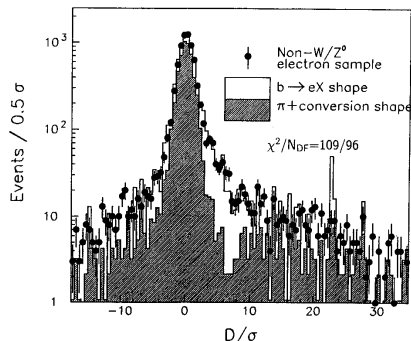


FIG. 25.  $D/\sigma$  of all electrons in the non- $W/Z^0$  electron sample, along with the expected shape from electrons from  $b$  decay and conversions + fake electrons (pions or multi-hadrons).

jet that the jet comes from the primary vertex of the event. Jets with low probability are likely to come from heavy quarks. This probability utilizes the signed impact parameters of the tracks in the jet, and is the probability that the impact parameters of the tracks are consistent with zero within the SVX resolution. The probability distribution for all jets (besides the electron jet) in the non- $W/Z^0$  electron sample is shown in Fig. 24. Heavy quark jets are identified as those jets with jet probability  $< 0.02$ . From the flat component under the probability peak in Fig. 24 backgrounds in this sample from false tags of the away jet are expected to be  $\sim 10\%$ . The  $b$  electron  $D/\sigma$  shape is estimated from these tagged events.

Figure 25 shows the  $D/\sigma$  distribution for the electrons in the non- $W/Z^0$  sample that go through the SVX. We fit the tails of the  $D/\sigma$  distribution to the sum of  $b$ , fake, and conversion shapes, with the conversion fraction fixed. We find

$$f_{\text{conv}} = 41.5 \pm 2.2\%,$$

$$f_b = 31.5 \pm 3.7\%,$$

$$f_{\text{fake}} = 27.0 \pm 4.4\%.$$

The dominant uncertainty on these fractions comes from the small statistics available to estimate the  $b$  electron shape.

### C. Estimate of fake electron fraction

This section provides a second, independent estimate of the fraction of the non- $W/Z^0$  electrons that are fake electrons. The fraction  $f_{\text{fake}}$  of Sec. IV B is the fraction of the electrons consistent with coming from the primary vertex, which we interpreted as misidentified hadrons from light quark jets. Hadrons may also be identified using the central preradiator, since in general they do not begin to shower in the solenoidal coil, while electrons do. Plotted in Fig. 26 is the CPR charge for all electrons in

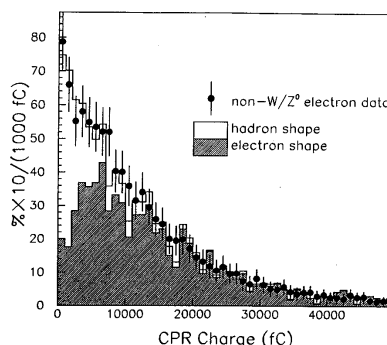


FIG. 26. CPR charge and shape for electrons and shape for hadrons.

the non- $W/Z^0$  sample. Also shown is the CPR shape for electrons (obtained from electrons in  $Z^0 \rightarrow e^+e^-$  decay) and hadrons (obtained from jets in  $W/Z^0 + \text{jet}$  events). With the conversion electron fraction fixed (see Sec. IV A) we fit the distribution to the sum of the two shapes to find

$$\begin{aligned} f_{\text{conv}} &= 41.5 \pm 2.2\%, \\ f_b &= 31.9 \pm 4.0\%, \\ f_{\text{fake}} &= 26.6 \pm 4.1\%. \end{aligned}$$

The agreement with Sec. IV C is good, since the two estimates are independent: in one method the zero lifetime of hadrons is used to differentiate them from heavy quark electrons, and in the other method the longitudinal shower development of electrons and hadrons is used.

#### D. Number of inclusive electrons from QCD jets

The non- $W/Z^0$  electron sample is postulated to originate from QCD processes producing hadron jets. One can ask the simple question what fraction of events in the overall inclusive electron sample (see Sec. III A) come from such QCD processes? This question is not crucial to this analysis, but is interesting.

Noting that electrons with  $I > 0.3$  are predominantly from QCD processes, we may use Fig. 20(a) to estimate a 58% efficiency of the  $\cancel{E}_T < 10$  GeV cut used to make the non- $W/Z^0$  sample for hadron jets. We then scale the 21 637 hadron jet events of Sec. III D up by this efficiency to obtain that approximately  $37\,000 \pm 4000$ , or  $(73 \pm 7)\%$ , of the 50 861 inclusive electrons are from hadron jets. The number 21 637, it was noted, has a  $\sim 1\%$  background from  $W/Z^0$  decay, but this can be neglected for

our present purposes.

Figure 27 shows the  $E_T$  spectrum of electrons in the inclusive electron sample, along with the spectrum from the non- $W/Z^0$  electron sample (scaled up to 37 000 events), and the Monte Carlo expectation for electrons from  $W/Z^0$  decays (normalized using the number of  $W$  and  $Z^0$  candidates). The events at the very highest  $E_T$  are mostly dijets, with one  $Z^0$  event. The apparent excess of events above 80 GeV is due to the truncation of the sample used to obtain the hadron dijet spectrum: the very highest  $E_T$  dijets will have some  $\cancel{E}_T$  due to mismeasurement, and the dijet shape comes from  $\cancel{E}_T < 10$  GeV sample. The conclusion from this study is that the inclusive electron data sample is adequately described by three sources: QCD hadron jets,  $W$  decays, and  $Z^0$  decays.

### V. W CANDIDATE SAMPLE

$W$  candidates are selected with a signature of an isolated electron and  $\cancel{E}_T$ . This signature, however, can also be mimicked by other physics processes. The physics processes described in Sec. IV can lead to backgrounds to the  $W$  signal if the hadron jet containing the electron fluctuates so that the electron is isolated in the calorimeters and if the other jet is mismeasured or falls into an uninstrumented region of the detector, creating  $\cancel{E}_T$ . Similarly, the decays  $Z^0 \rightarrow e^+e^-$  or  $Z^0 \rightarrow \tau^+\tau^- \rightarrow e^\pm \nu \nu X$  can be misidentified as  $W$ 's if one electron is detected and the other lepton falls in an uninstrumented region or the neutrinos from  $\tau$  decays are sufficiently energetic. This section discusses the backgrounds to the  $W$  signal from these processes.

#### A. W candidate selection

The  $W$  candidate selection is described in Sec. III C but is briefly summarized here. To select  $W$ 's we (a) require a tight, isolated central electron in the event, (b) require  $\cancel{E}_T > 20$  GeV, and (c) reject events with second, isolated, electromagnetic clusters which form a mass with the first electron in the 66–116 GeV/ $c^2$  range. A total of 13 796 events have  $\cancel{E}_T > 20$  GeV and fail our  $Z^0$  cuts. As shown in Fig. 20, the missing transverse energy of the isolated electrons shows the characteristic peak, while the nonisolated electrons pile up at threshold. The problem now is to calculate the background under the peak in Fig. 20(b) with missing  $E_T > 20$  GeV.

#### B. Background from hadron jets

The background from hadron jets is estimated by extrapolating the isolation variable for the electron from a region away from the  $W$  signal into the  $W$  signal region. We identify four regions within the plot of  $I$  vs missing  $E_T$  in Fig. 19: (1) isolation  $< 0.1$  and  $\cancel{E}_T < 10$  GeV, at least one other jet; (2) isolation  $> 0.3$  and  $\cancel{E}_T < 10$  GeV,

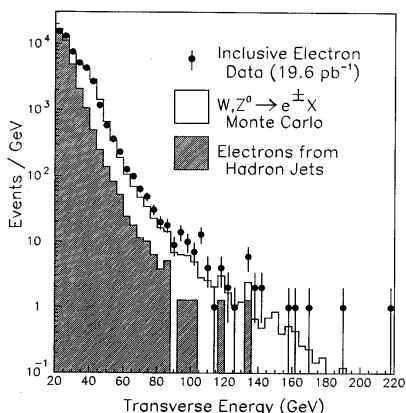


FIG. 27.  $E_T$  spectrum of electrons in the inclusive electron sample and spectrum from the non- $W/Z^0$  electron sample.

at least one other jet; (3) isolation  $> 0.3$  and  $\cancel{E}_T > 20$  GeV; (4) isolation  $< 0.1$  and  $\cancel{E}_T > 20$  GeV. [Region (4) is the  $W$  signal region.] The requirement of one other jet in regions (1) and (2) is that one jet besides the jet containing the electron exists in the event. We find the  $W$  background from the equation

$$\frac{W \text{ background}}{\text{No. events in region (3)}} = \frac{\text{No. events in region (1)}}{\text{No. events in region (2)}}.$$

The motivation of the method is that electrons from hadron jets are generally produced embedded in a jet of other particles while electrons from  $W$  and  $Z^0$  decay are isolated. The equation above amounts to using the electrons with  $\cancel{E}_T < 10$  GeV in Fig. 28(a) to determine the  $I$  shape of electrons in hadron jets and then normalizing to the  $I > 0.3$  tail at  $\cancel{E}_T > 20$  GeV [Fig. 28(b)].

The requirement of at least one jet besides the electron jet in regions (1) and (2) is intended to account for the fact that the isolation of the electron on the one side of the QCD jet events is correlated with the magnitude of the jet  $E_T$  on the other side of the event, as is shown in Fig. 29. In the case of the dijet events which fake a  $W$ , the mismeasured jet  $E_T$  must be large in order to create a large  $\cancel{E}_T$ . Because the actual value of the mismeasured jet's  $E_T$  is unknown, we average the value of  $r \equiv (\text{No. of events with } I < 0.1) / (\text{No. of events with } I > 0.3)$  from two different subsets of the QCD ( $\cancel{E}_T < 10$  GeV) sample which have different opposing jet  $E_T$ 's:

Control sample 1: Events with a jet  $> 10$  GeV and EM fraction  $< 0.8$ ;

Control sample 2: Events with a jet  $> 20$  GeV and EM fraction  $< 0.8$ ;

(both have  $\cancel{E}_T < 10$  GeV).

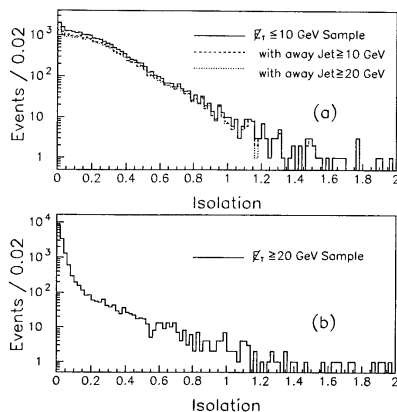


FIG. 28. Iso of the central electron in (a) the  $\cancel{E}_T < 10$  GeV sample; (b) the  $\cancel{E}_T > 20$  GeV sample. In (a) are also shown the isolation of the electron for the two subsets of the  $\cancel{E}_T < 10$  GeV sample with an additional jet besides the electron jet with  $\cancel{E}_T < 10$  and  $20$  GeV.

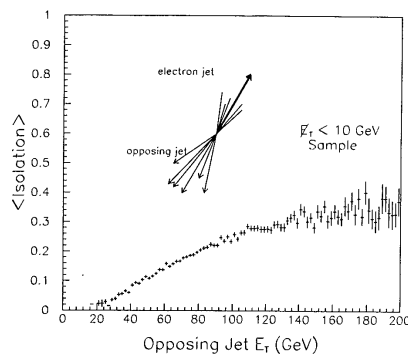


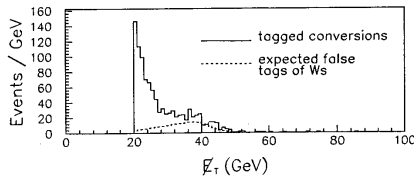
FIG. 29. Mean electron  $I$  vs  $E_T$  of the opposing jet in the  $\cancel{E}_T < 10$  GeV region. As the jet opposing the electron jet stiffens, momentum balance requires the particles in the electron jet to stiffen. They are thus less likely to be bent out of the  $I$  cone by the magnetic seal.

Control sample 2 is a subset of control sample 1. The control samples give  $r = 1.5$  (control sample 1) and  $r = 2.0$  (control sample 2). We average the results, obtaining  $\langle r \rangle = 1.8 \pm 0.3$ , to account for any systematic difference between the samples.

The hadron jet background is calculated as follows. There are 499 events in region (3), so multiplying  $\langle r \rangle$  gives  $W$  background  $= \langle r \rangle \times 499 = 898 \pm 155$  events. Given the 13 796  $W$  candidates, this is a 6.5% background contribution from electrons from hadron jets. Note in Fig. 20 the  $\cancel{E}_T$  shape of the events in region (3). Most of the  $W$  background piles up at the threshold of our missing  $E_T$  cut.

### C. Cross-check of hadron jet background

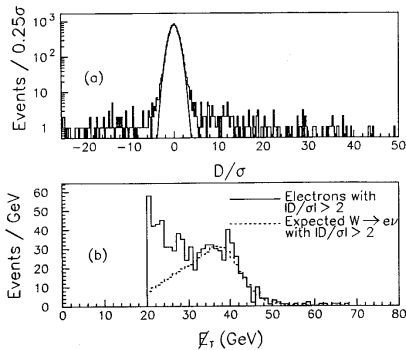
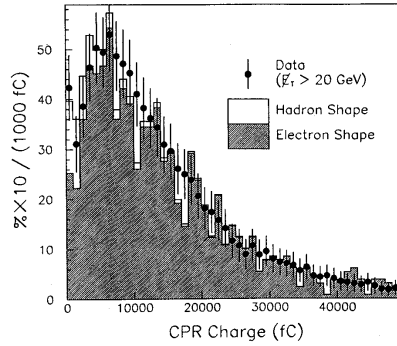
We check the method described in Sec. VB by estimating the background from individual jet contributions separately—photon conversions,  $b$  decays, and fake electrons from hadron showers—and then adding them up to find the total jet background to the  $W$ 's. This decomposition was applied to the non- $W/Z^0$  electron sample in Sec. IV. The non- $W/Z^0$  electron sample was selected from the total by requiring each event to have a jet with  $E_T > 10$  GeV and  $\cancel{E}_T < 10$  GeV. No isolation cut was applied to these data, because it would have greatly reduced the sample size, leaving too few events for further study. In order to compare the  $W$ 's to the background, the  $I$  cut is removed from the  $W$  sample, which adds 1433 events to the 13 796 events with  $\cancel{E}_T > 20$  GeV and  $I < 0.1$ , resulting in 15 229 events with  $\cancel{E}_T > 20$  GeV alone. About 2/3 of these extra events are background, and 1/3 is signal: Table X gives the efficiency of the  $I$  cut of 97%; hence one expects that of the additional 1433 events added to the  $W$  sample,  $0.03 \times 14\,000 = 420$  are really  $W$ 's.

FIG. 30.  $E_T$  of the flagged conversions.

To estimate the conversion contamination of the  $E_T > 20$  GeV region, we identify conversions by searching for the partner track to the electron using the  $\delta(r-\phi)$  and  $\delta(\cot\theta)$  cuts from Sec. IV A. Using the efficiency and correcting for the overefficiency of the conversion-finding cuts, we estimate that there are  $910 \pm 90$  events with  $E_T > 20$  GeV that are conversion pairs. The  $E_T$  of the flagged conversions is shown in Fig. 30.

To estimate the contamination to the  $E_T > 20$  GeV region from  $b$  electrons we employ the impact parameter method described in Sec. IV B. In Fig. 31(a) is plotted the signed impact parameter significance for the electrons with  $E_T > 20$  GeV. In Fig. 31(b), we show the  $E_T$  distribution of the electrons with  $|D/\sigma| > 2$ . There is a bump at 40 GeV, which indicates that some  $W$  electrons have a large impact parameter significance, simply due to resolution effects. Using electrons from  $Z^0 \rightarrow e^+e^-$  decays to estimate number of  $W$ 's in the  $D/\sigma$  tails due to resolution effects, we superimpose the expected  $E_T$  for  $W$  electrons. We find that  $850 \pm 360$  events with  $E_T > 20$  GeV are from heavy quarks.

To estimate the contamination to the  $E_T > 20$  GeV

FIG. 31. (a) Plot of the signed impact parameter significance for electrons with  $E_T > 20$  GeV. (b)  $E_T$  distribution of the electrons with  $|D/\sigma| > 2$ .FIG. 32. CPR charge of  $E_T > 20$  GeV electrons, along with the expected shape of electrons and the shape for hadrons.

region from misidentified hadrons, we use the charge deposited in the CPR, shown in Fig. 32. Also shown is the expected shape for good electrons and for hadrons. We estimate that there are  $580 \pm 370$  of the 15229 events with  $E_T > 20$  GeV which are really hadron fakes.

Adding these numbers, there are  $910 \pm 90$  conversions,  $850 \pm 360$   $b$  electrons, and  $580 \pm 370$  hadron fakes for a grand total of  $2340 \pm 530$  hadron jet background events obtained by application of the analyses described in Sec. IV applied to the  $W$  sample itself. Within the quoted uncertainties, this number is consistent with the  $I < 0.1$  number of  $898 \pm 155$  background events quoted in Sec. V B plus an extra  $1433 - 420 \approx 1000$  events background from relaxing the  $I$  cut.

An independent method of estimating the total jet background in the  $E_T > 20$  GeV sample with the  $I$  cut relaxed, that is to check that the extra 1000 added background events are reasonable, is to use the  $I$  vs  $E_T$  extrapolation technique of Sec. V B again. First, we define  $R \equiv (\text{all } I \text{ electrons}) / (I > 0.3)$  for hadron jet electrons in the  $E_T < 10$  GeV sample. This ratio, averaging over the two control samples 1 and 2, is  $\langle R \rangle = 4.2 \pm 0.7$ . Multiplying this ratio by the number of events in region (3) obtained in Sec. V B gives  $2100 \pm 350$  events. Within the uncertainties, this direct extrapolation result and the  $2340 \pm 530$  events obtained by adding up the three components are consistent. This analysis supports the  $898 \pm 155$  background number with  $I < 0.1$ , which will be subtracted from the  $W$  sample to calculate the  $W/Z^0$  cross section ratio.

#### D. Background from $Z^0 \rightarrow e^+e^-$

##### 1. $Z^0 \rightarrow e^+e^-$ background estimate

We use the ISAJET Monte Carlo program and a detailed detector simulation to determine the background

to the  $W$ 's from  $Z^0 \rightarrow e^+e^-$  decays that mimic the  $W$  signature. We find that  $18 \pm 2\%$  of all  $Z^0 \rightarrow e^+e^-$  decays where the first leg is reconstructed in the central region will mimic  $W$ 's. We normalize this rate to the observed number of  $Z^0$  candidates, which avoids the systematic uncertainties of normalizing to the measured [26] cross section times branching ratio  $\sigma B(p\bar{p} \rightarrow Z^0 \rightarrow e^+e^-)$  at  $\sqrt{s} = 1800$  GeV. The background to the  $W$ 's from  $Z^0 \rightarrow e^+e^-$  decays is  $281 \pm 32$  events.

## 2. $Z^0 \rightarrow e^+e^-$ background cross-check

The ISAJET Monte Carlo program is used to determine several of the  $W$  backgrounds, so its performance is checked using  $Z^0 \rightarrow e^+e^-$  decays. We can recover some of the 18% of  $Z^0 \rightarrow e^+e^-$  decays by looking for the charged track of the second electron in the central tracking chamber. In the central region, the second electron is typically not observed in the calorimeter because it goes through a  $\phi$  crack or the  $\theta = 90^\circ$  crack or the chimney module. Its charged track is nonetheless detected with 99.7% efficiency in the CTC if it passes through all 8 superlayers. ISAJET studies indicate that  $81 \pm 12$  events of the 281  $Z^0$ 's that fake  $W$ 's should be detectable as having a track with  $P_T > 10$  GeV/c, even though the calorimeter cluster is not observed.

In our  $W$  sample, we search for second, isolated tracks in the CTC which come from the same primary vertex as the " $W$  electron" and which have  $P_T > 10$  GeV/c. If the track extrapolates to a region in the calorimeter where energy is deposited, the electromagnetic fraction is required to be  $> 0.8$ . Approximately 3800 events in the  $W$  sample are observed to have a high- $P_T$  track, and 904 of these come from the same primary vertex, are

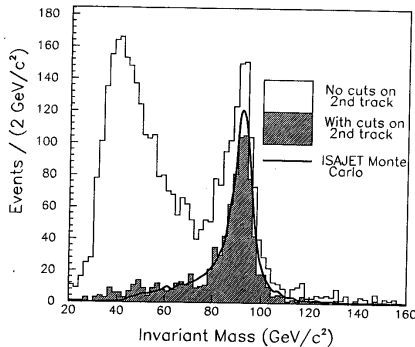


FIG. 33. Invariant mass of the tight central electron and the second high- $P_T$  track, both with and without the cuts on the second track (see text). The long tail below the  $Z^0$  mass is due to the photons radiated away by the second electron track.

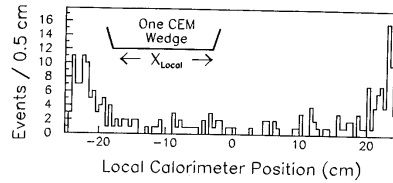


FIG. 34. Local calorimeter position of the second track in  $Z^0 \rightarrow e^+e^-$  candidates within the  $W$  sample when no second calorimeter cluster is observed.

isolated, and point to possible electromagnetic energy. Figure 33 shows the electron + track invariant mass of the 3800 and 904 events. Also shown is the expected shape from ISAJET. In 213 events, there is  $\cancel{E}_T > 20$  GeV, and in 83 of the 213 events no second electron cluster (as defined in Sec. IIB) is observed. This compares well to the  $81 \pm 12$  events predicted by ISAJET. Figure 34 shows that when  $\cancel{E}_T > 20$  GeV, the second track tends to point to a calorimeter  $\phi$  crack.

## E. Background from $Z^0 \rightarrow \tau^+\tau^-$

The process  $Z^0 \rightarrow \tau^+\tau^-$  can mimic the  $W$  signature if one  $\tau$  decays to an electron. Using ISAJET and a detector simulation and normalizing to the observed  $Z^0 \rightarrow e^+e^-$  yield, we find the background from this process to be  $48 \pm 7$  events.

## F. Background from $W \rightarrow \tau\nu$

The process of  $W$  bosons decaying to  $\tau\nu$ , where the  $\tau$  then decays leptonically to an electron, can also produce a high  $P_T$  electron in the central region with large  $\cancel{E}_T$ . We similarly use ISAJET to estimate the acceptance for this process but normalize instead to the ISAJET  $W \rightarrow e\nu$  acceptance and the observed number of  $W \rightarrow e\nu$  events. We find the background from  $W \rightarrow \tau\nu$  to be  $473 \pm 29$  events. This normalization avoids the uncertainties introduced by using the luminosity and the previously measured  $W$  cross section [26].

## G. Background from a heavy top quark

The background of real  $W$ 's produced from a heavy top quark is considered. Direct searches [1] for the top quark have to date given evidence for its existence, but we take this background to be 0, with an error given by the number of events expected for a  $130$  GeV/ $c^2$  top quark, which is the 95% confidence level limit [1,2] on its mass. This prescription for the top quark background leads to the most conservative limit on new decay modes obtained with the  $W$  leptonic branching ratio extracted

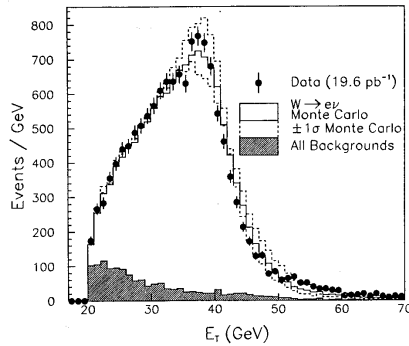


FIG. 35. Electron  $E_T$  in  $W \rightarrow e\nu$  decays. The background contributions are described in Sec. V and the  $W$  shape is determined using the Monte Carlo program described in Sec. VII. The uncertainty in the Monte Carlo program is the spread resulting from the uncertainty on the  $W$  boson  $P_T$  shape that is input to the Monte Carlo program.

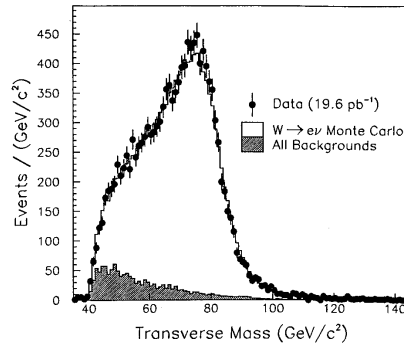


FIG. 37. Transverse mass of  $W \rightarrow e\nu$  decays. The background contributions are described in Sec. V and the  $W$  shape is determined using the Monte Carlo program described in Sec. VII.

from the  $W/Z^0$  cross section ratio. Using the ISAJET Monte Carlo, we find the expected background from a heavy top quark is  $0^{+40}_{-0}$  events. While a  $130 \text{ GeV}/c^2$  top quark would contribute 40 events background, a  $150 \text{ GeV}/c^2$  top quark would lead to an expected background of 19 events and a  $175 \text{ GeV}/c^2$  top quark [2] would lead to 9 events background.

#### H. Summary of $W$ signal, backgrounds

In Figs. 35–37 we plot the electron  $E_T$ , the  $\cancel{E}_T$ , and the transverse mass of the  $W$  candidates, along with the

background estimates and the expectations of the Monte Carlo program described in Sec. VII. The agreement of the shapes of all of these distributions gives further confidence in the background estimates presented here. The measured  $W P_T$  distribution which is input to the Monte Carlo program is not sufficiently accurate to provide a precise Monte Carlo prediction for the electron  $E_T$  distribution, as reflected in Fig. 35. The  $\cancel{E}_T$  is in principle sensitive to the boson  $P_T$  as well, but the neutrino resolution is poor enough so that the shape mismatch is less noticeable. The transverse mass distribution is insensitive to the boson  $P_T$ .

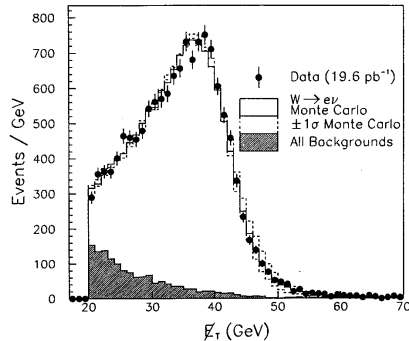


FIG. 36.  $\cancel{E}_T$  of  $W \rightarrow e\nu$  decays. The background contributions are described in Sec. V and the  $W$  shape is determined using the Monte Carlo program described in Sec. VII. The uncertainty in the Monte Carlo program is the spread resulting from the uncertainty on the  $W$  boson  $P_T$  shape that is input to the Monte Carlo program.

### VI. $Z^0$ CANDIDATE SAMPLE

The signature used to select  $Z^0 \rightarrow e^+e^-$  candidates is an isolated, tight central electron plus a second, loosely selected electromagnetic cluster. Very few processes mimic the signature of two high- $P_T$  electron clusters. Thus, while the  $W \rightarrow e\nu$  candidate sample had backgrounds from other processes totaling approximately 12% of the observed candidates, the backgrounds to the  $Z^0$  candidates are observed to total less than 2%.

#### A. $Z^0$ candidate selection

$Z^0$  candidates are selected from the inclusive electron sample by requiring an isolated tight central electron and a second isolated electron which passes loose selection criteria. The cuts on the tight electron are summarized in Table V and for the second electron in Table VI. Figure 17 shows the invariant mass spectrum of electron pairs passing these cuts. We observe 1312 events which fall in the  $66\text{--}116 \text{ GeV}/c^2$  mass range.



### B. Background from hadron jets

Hadron jet events can fake the signature of a  $Z^0$  decay into electrons if two of the jets fluctuate in such a way as to fake electrons. As with the hadron jet background to  $W$ 's, we attempt to measure the hadron jet background to  $Z^0$ 's from the data by extrapolating the isolation distribution of the electrons. Figure 38 shows the electron-positron invariant mass vs the isolation of the second electron, where the isolation cut of Table VI has been removed. While there is an unambiguous cluster at the  $Z^0$  mass and low isolation, some background events in the  $Z^0$  mass window extend as far as  $I = 1.4$ .

We posit that all events with  $I > 0.3$  on either leg are background from hadron jets. This assumption is equivalent to assuming that an isolation cut of 0.3 is 100% efficient for electrons from  $Z^0$ 's. This is quite reasonable, since in Fig. 4(g) none of the 9000  $W$  electrons have  $I > 0.14$ . We divide the electron pairs into four regions: (1) events with  $I_1 < 0.1$  and  $I_2 < 0.1$ ; (2) events with  $I_1 < 0.1$  and  $I_2 > 0.3$ ; (3) events with  $I_1 > 0.3$  and  $I_2 < 0.1$ ; (4) events with  $I_1 > 0.3$  and  $I_2 > 0.3$ . None of samples (2)–(4) have a  $Z^0$  peak. The  $Z^0$  background is calculated from the equation

$$\frac{Z^0 \text{ background}}{\text{No. events in region (2)}} = \frac{\text{No. events in region (3)}}{\text{No. events in region (4)}}.$$

We find that there are  $20 \pm 9$  events background to the  $Z^0$  candidates due to hadron jets. We find that  $0^{+1}_{-0}$  of these come from the central-central  $Z^0$ 's, whereas the plug region contributes  $14 \pm 14$  events background and the forward region contributes  $6 \pm 3$  events background.

In the central region, the same-sign electrons serve as a cross-check of background estimated by the  $I$  extrapolation method. Background would likely have equal numbers of same- and opposite-sign events. This hypothesis

is supported by the fact that most nonisolated same-sign pairs have  $|\delta x| > 2$ , indicating a poor match between the track and the EM shower, as characteristic of overlaps of  $\pi^+$  and  $\pi^0$  showers, and not  $b$  electron pairs ( $b$  electron pairs would have  $|\delta x| < 2$ , and would be mostly oppositely signed, with only  $\approx 30\%$  same sign). There are 3 central-central same-sign  $e^\pm e^\pm$  pairs in the mass window passing all our cuts, to be compared with the  $I$  estimate of  $0^{+1}_{-0}$  central-central background events.

### C. Background from $Z^0 \rightarrow \tau^+ \tau^-$

The production of  $Z^0 \rightarrow \tau^+ \tau^-$  can fake  $Z^0 \rightarrow e^+ e^-$  decay if both taus decay via  $\tau \rightarrow e \nu \nu$  and if the electrons form an invariant mass in the 66–116  $\text{GeV}/c^2$  invariant mass range. We use the ISAJET Monte Carlo program and a detector simulation to estimate that the background due to  $Z^0 \rightarrow \tau^+ \tau^-$  as  $1 \pm 1$  event.

### D. Background from the Drell-Yan process

We apply a correction to the number of  $Z^0$  candidates to account for the fact that some  $e^+ e^-$  pairs in the 66–116  $\text{GeV}/c^2$  mass range come from continuum  $p\bar{p} \rightarrow \gamma^* \rightarrow e^+ e^-$ , and not resonant  $Z^0$  production. The correction is applied so our result is consistent with theoretical calculations, which typically use only the  $Z^0$  amplitude, and not the  $\gamma^*$  term or the  $Z^0$ - $\gamma^*$  interference term. We include in our Monte Carlo program described in Sec. VII both the  $Z^0$  and  $\gamma^*$  amplitudes to determine the number of the events in our mass window from continuum Drell-Yan production. This correction also takes into account the effect of the mass window cut, since this is not accounted for in the Monte Carlo results of Sec. VII. We compute the integrals  $I_1 = \int_{66}^{116} |Z^0 + \gamma|^2 dM$

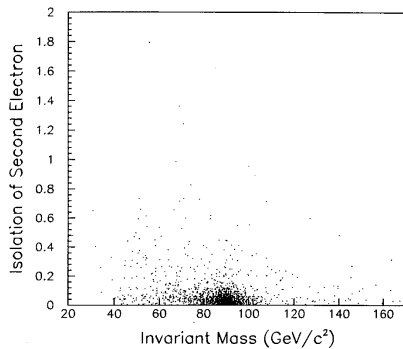


FIG. 38. Invariant mass of the two electrons vs the  $I$  of the second electron.

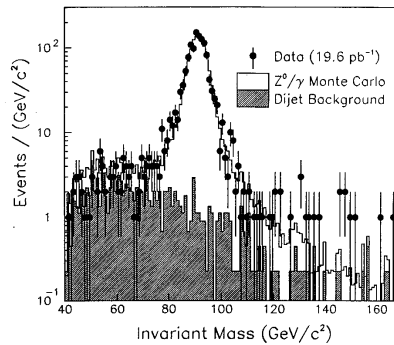


FIG. 39. Invariant mass of  $Z^0 \rightarrow e^+ e^-$  decays. The background contributions are described in Sec. VI and the  $Z^0$  shape is determined using the Monte Carlo program described in Sec. VII. Both  $Z^0$  and Drell-Yan photon terms are included.

and  $I_2 \equiv \int_0^\infty |Z^0|^2 dM$ . The number of  $Z^0$  candidates must be divided by the number  $I_1/I_2$ , which we find to be  $1.005 \pm 0.002$ .

### E. Comparison of $Z^0$ signal, backgrounds

Finally, in Fig. 39 we show the invariant mass distribution for the  $e^+e^-$  candidates, along with the shape for the  $Z^0 + \gamma^*$ , and the expected hadron jet background shape. The  $Z^0 + \gamma^*$  signal shape is derived from the Monte Carlo program described in Sec. VII. The background shape is derived from “dielectrons” in region (2) described in Sec. VIB above, and is normalized to have 20 events in the mass range 66–116 GeV/ $c^2$ . The signal Monte Carlo program is normalized to 1291 events in the 66–116 GeV/ $c^2$  interval.

## VII. ACCEPTANCES

We use a Monte Carlo program to determine the ratio,  $A_W/A_Z$ , of the kinematic and geometric acceptances  $A_W$  and  $A_Z$ . The kinematic portion of the acceptance is the efficiency of  $W$  and  $Z^0$  events to pass our  $P_T$  cuts on the leptons, and the geometric portion of the acceptances is the efficiency for the leptons to fall into the parts of the detector accepted as part of our fiducial volume. Note that, because of the requirement of at least one electron in the central region common to both  $W$  and  $Z^0$  decays, the problem of determining  $A_W/A_Z$  reduces to modeling the difference in the acceptance of the second lepton only, viz., the electron or neutrino.

The Monte Carlo program is also used to determine the relative acceptances of the central, plug, and forward detector regions for electrons from  $Z^0 \rightarrow e^+e^-$  decays. For those  $Z^0$ 's with at least one electron that falls in the central detector region, we calculate the fractions  $F_{cc}$ ,  $F_{cp}$ , and  $F_{cf}$  of  $Z^0$ 's where the second electron falls in the central, plug, and forward regions. These fractions will be used in Sec. VIII.

### A. Description of the Monte Carlo program

The Monte Carlo program generates  $W$ 's and  $Z^0$ 's using the lowest order diagram,  $q\bar{q} \rightarrow W(Z^0)$ . No quark-gluon diagrams or initial-state radiation are considered. The boson masses are generated according to a relativistic Breit-Wigner distribution. In order to mimic the effects of higher-order diagrams, the bosons are given a  $P_T$  according to the measured [27]  $W$   $P_T$  distribution in  $pp$  collisions at  $\sqrt{s} = 1.8$  TeV. The leptons are propagated to the calorimeter and their momenta are smeared according to the nominal detector resolutions. The electrons in our Monte Carlo program are required to propagate to a fiducial region of the detector.

The electron resolution in the simulation is  $(\sigma/E)^2 = \frac{(13.5\%)^2}{E(\text{GeV})} + (2 \pm 1\%)$ , where the energy-independent term of  $(2 \pm 1)\%$  represents tower-to-tower variations in the

energy scale calibrations and is measured using the observed width of the  $Z^0 \rightarrow e^+e^-$  resonance. A model is also made for the  $\cancel{E}_T$  resolution. Since the neutrino transverse momentum is inferred from momentum conservation, the  $\cancel{E}_T$  measurement is dominated by the electron, but is also sensitive to the calorimeter response to the hadrons which recoil against the  $W$ . In this model, we use a parametrization of the smearing on the component of the  $\cancel{E}_T$  parallel and perpendicular to the  $P_T$  of the boson as a function of the boson  $P_T$  which is obtained from a detailed simulation of the detector. Using the parameters  $M_W = 80.21$  GeV/ $c^2$ ,  $M_Z = 91.18$  GeV/ $c^2$ , and the Martin-Roberts-Stirling set  $D'_-$  (MRS  $D'_-$ ) parton distribution functions [28] we find  $A_W = 0.3416 \pm 0.0008$  and  $A_Z = 0.4120 \pm 0.0008$ , where the errors are statistical only. Note that, because central-central  $Z^0$ 's have two chances of having one electron in the central detector region, the  $Z^0$  acceptance is higher. The fractions  $F_{cc}$ ,  $F_{cp}$ , and  $F_{cf}$ , are found to be 0.372, 0.509, and 0.120, respectively.

### B. Systematic uncertainties in $A_W/A_Z$

In this section, we investigate the systematic uncertainties due the choice of parton distribution functions (PDF's), the underlying event model, the boson masses, the calorimeter energy scales, the  $P_T$  distribution input to the Monte Carlo program, and higher-order diagrams. For each possible source of systematic uncertainty, we repeat the Monte Carlo calculation with different values for these parameters and take the error to be one-half of the spread in the results. As is discussed below, while the individual acceptances are sensitive to variations in these parameters, the ratio is more stable. In the tables which follow, all of the values for  $W$  and  $Z^0$  acceptances have a statistical error of  $\pm 0.0008$ .

In order to estimate the systematic uncertainty due to the parton distribution functions, we employ different sets of PDF's not excluded by current experimental data. We find a 0.9% uncertainty in  $A_W/A_Z$  due to PDF's as shown in Table VIII.

The acceptances depend upon the  $W$  mass through the lepton  $P_T$ 's. Using  $M_Z = 91.18$  GeV/ $c^2$ , and MRS  $D'_-$  PDF's we find a 0.1% uncertainty in  $A_W/A_Z$  when  $M_W = 80.2 \pm 0.2$  GeV/ $c^2$  is varied within its uncertainty,

TABLE VIII. Acceptances calculated with different parton distribution functions.

PDF	$A_W$	$A_Z$	$A_W/A_Z$
MRS $D'_-$	0.3416	0.4102	0.833
MRS $D_0'$	0.3458	0.4133	0.837
MRS $S_0'$	0.3486	0.4118	0.847
CTEQ 1M	0.3522	0.4137	0.851
CTEQ 1MS	0.3517	0.4152	0.847
CTEQ 1L	0.3422	0.4096	0.835
CTEQ 1ML	0.3533	0.4159	0.849
Uncertainty:	0.0059	0.0029	0.009

as shown in Table IX.

The measurement of the  $W$  boson  $P_T$  spectrum [27] has sufficiently large uncertainties that the variations in its shape allowed by the measurement lead to variations in the boson acceptances. To estimate the systematic uncertainty due to the input boson  $P_T$  distribution, we take the “nominal”  $P_T$  distribution to be the measured spectrum, the “soft”  $P_T$  distribution to be the distribution one gets when varying the nominal by one sigma in each bin so as to give a more steeply falling spectrum (deforming about the point  $P_T = 16$  GeV/c), and the “hard” distribution to be the shape that one gets by varying by one sigma so as to get a more slowly falling spectrum. Trying these three shapes for the  $P_T$  choice, we find a 0.2% variation in  $A_W/A_Z$ , as shown in Table IX.

It has been assumed that the  $W$  and  $Z^0$  have the same  $P_T$  spectra. Experimental measurements of these spectra are consistent with this assumption [29]. Theoretical calculations [30] indicate that the differences are expected to be less than 2%. If we assume that the spectra are different, and use calculations [31] of their individual  $P_T$  spectra, we introduce an extra uncertainty from this effect of  $\pm 0.0005$ , which is negligible compared to the  $\pm 0.0020$  uncertainty from our knowledge of the  $W$   $P_T$  spectrum.

The electron energy scale in the data is set for this analysis using  $Z^0 \rightarrow e^+e^-$  decays to an accuracy of approximately 0.2%. We vary the energy scale of the central calorimeters in the simulation by 0.2% and summarize the variations in  $A_W/A_Z$  in Table IX. Variations in the plug detector energy scale cause similar variations in  $A_W/A_Z$ , while variations in the forward detector energy scale result in 0.2 times this variation in  $A_W/A_Z$  because the forward detector has 0.2 times the acceptance of the central and plug. The uncertainty in  $A_W/A_Z$  due to the energy scale is estimated to be 0.3%.

We also estimate the systematic uncertainty on  $A_W$  due to the model of the  $\cancel{E}_T$  resolution. We have, in addition to the simulation-based model, estimated the acceptances with two other models of the resolution. One model [32] utilizes parametrizations of the calorimeter response to hadrons obtained from a sample of minimum bias triggers, where  $\cancel{E}_T$  is dominated by calorimeter response, not neutrinos. The other model [33] uses  $Z^0 \rightarrow e^+e^-$  data to measure the calorimeter response as a function of boson  $P_T$ . Again, in  $Z^0$  events, observed  $\cancel{E}_T$  is dominated by the response to hadrons which recoil against the  $Z^0$ . This new method would in principle

be the best model to use, but we lack adequate statistics in the  $Z^0$ 's at high  $P_T$ , where the  $\cancel{E}_T$  smearing is the largest. We find a 0.5% uncertainty in  $A_W/A_Z$  due to the choice of the  $\cancel{E}_T$  resolution model, as shown in Table IX.

Finally, we investigate the assumption that  $A_W/A_Z$  is insensitive to higher-order diagrams. It is likely that the ratio of acceptances is insensitive to QCD corrections, since one chooses a common leg in the central region and then the only thing that can change the ratio is a difference in the  $\eta$  distribution of the second lepton for  $W$ 's and  $Z^0$ 's. With the LO Monte Carlo the  $\eta$  distribution of leptons seems well modeled (see Figs. 18 and 21). We have employed a Monte Carlo program which incorporates a next-to-leading order (NLO) calculation by Giele *et al.* [34]. The events from this generator are fed through the same detector simulation as with the LO Monte Carlo program so as to minimize differences in the comparison. The difference in results is taken as the systematic uncertainty. The results are shown in Table IX.

#### C. Effects of radiative corrections

The effects of radiative decay,  $Z^0 \rightarrow e^+e^-\gamma$  or  $W \rightarrow e\nu\gamma$ , are largely accounted for in our calculations of the  $E/p$  and  $I$  efficiencies for electrons (see Sec. VIII), since most radiated photons tend to be collinear with one of the electrons in  $W$  or  $Z^0$  decay. In addition, the radiated photons tend to shift the lepton  $P_T$ 's downward, but this shift is largely common to both  $W$ 's and  $Z^0$ 's, and hence cancel in the ratio of cross sections. A residual effect in the cross-section ratio due to photons radiated at wide angles to the electrons is that the observed  $e^+e^-$  pair mass from  $Z^0$  decays is shifted downward. We use a Monte Carlo program [35] with the full matrix elements for radiative decay to find that  $0.3 \pm 0.2\%$  of  $Z^0$ 's fall outside of the 66–116 GeV/ $c^2$  mass window after the kinematic cuts are applied. Correcting for this loss of acceptance shifts the result for  $A_Z$  from 0.4102 to 0.4090 and  $A_W/A_Z$  from 0.833 to 0.835.

#### D. Summary of acceptance results

Incorporating all the systematic shifts and uncertainties quoted above, we find, for the acceptances,

$$\begin{aligned} A_W &= 0.342 \pm 0.001 \text{ (stat)} \pm 0.008 \text{ (syst)} , \\ A_Z &= 0.409 \pm 0.001 \text{ (stat)} \pm 0.005 \text{ (syst)} , \\ A_W/A_Z &= 0.835 \pm 0.001 \text{ (stat)} \pm 0.013 \text{ (syst)} . \end{aligned}$$

Using the Monte Carlo to calculate the fractions  $F_{cc}$ ,  $F_{cp}$ , and  $F_{cf}$  of  $Z^0$ 's with one leg in the central that have the second leg in the central, plug, or forward, respectively, we find

$$\begin{aligned} F_{cc} &= 0.372 \pm 0.001 \text{ (stat)} \pm 0.007 \text{ (syst)} , \\ F_{cp} &= 0.509 \pm 0.001 \text{ (stat)} \pm 0.007 \text{ (syst)} , \\ F_{cf} &= 0.120 \pm 0.001 \text{ (stat)} \pm 0.004 \text{ (syst)} . \end{aligned}$$

TABLE IX. Systematic uncertainties in the boson acceptances.

Effect	$\delta A_W$	$\delta A_Z$	$\delta(A_W/A_Z)$
PDF's	0.0059	0.0029	0.009
$M_W$	0.0004	0.001	0.001
Boson $P_T$	0.0019	0.0013	0.002
Energy scale	0.0004	0.0030	0.003
Neutrino model	0.0020		0.005
NLO diagrams	0.0010	0.0030	0.006
Total uncertainty:	0.008	0.005	0.013

It is important to note that the uncertainty in the ratio of acceptances is smaller than the sum in quadrature of the uncertainties in the individual  $W$  and  $Z^0$  acceptances. This smaller uncertainty is partially the result of the method of requiring a common central electron for  $W$  and  $Z^0$  decays which decreases our sensitivity to many of the systematic effects discussed in this section.

### VIII. EFFICIENCIES

This section concerns the efficiencies of the leptons from  $W$  and  $Z^0$  decays to pass the electron selection criteria described in Sec. III and to pass the electron trigger. To estimate these efficiencies, we select a sample of high  $P_T$  electrons unbiased by the cuts whose efficiencies we wish to estimate. The high  $P_T$  electrons we use come from  $W$  and  $Z^0$  decay, but are selected with criteria different from those used in Sec. III.

We identify 5 efficiencies which must be measured: (1) the efficiency, which we call " $c_1$ ," for a central electron in the fiducial region from  $W$  or  $Z^0$  decay to pass the tight cuts; (2) the efficiency " $c_2$ " for the second leg of a  $Z^0$  in the fiducial central region to pass the loose central cuts; (3) the efficiency " $p$ " for the second leg of a  $Z^0$  in the plug region to pass the loose plug cuts; (4) the efficiency " $f$ " for the second leg of a  $Z^0$  in the forward region to pass the loose forward cuts; and finally (5) the efficiency " $\epsilon_T$ " of a central electron from  $W$  or  $Z^0$  decay which passes the tight  $c_1$  cuts to pass the electron trigger.

The electron identification efficiencies are measured using the second leg of  $Z^0$  events. The  $Z^0$  events are selected with tight cuts on the first central leg and then requiring a second electromagnetic cluster that has an invariant mass with the first in a tight window around the  $Z^0$  mass. No further identification cuts are used on the second leg. Efficiencies are then measured by observing what fraction of the  $Z^0$  second electrons pass the identification cuts.

#### A. Tight central identification efficiency $c_1$

We select a sample of central-central  $Z^0$ 's which satisfy the following requirements on the event: One leg passes

TABLE X. Efficiency of the tight central cuts.

Cut	Efficiency (%)
Had/EM	$100.0^{+0.0}_{-0.5}$
$I$	$97.3 \pm 0.5$
$L_{shr}$	$98.0 \pm 0.4$
$E/p$	$95.0 \pm 0.7$
$\delta x$	$94.1 \pm 0.8$
$\delta z$	$98.2 \pm 0.4$
$\chi^2_{strip}$	$95.0 \pm 0.7$
All cuts	$85.1 \pm 1.1$
Tracking, $E/p$ corrections	$99.2 \pm 0.4$
$c_1$ efficiency	$84.5 \pm 1.2$

TABLE XI. Efficiency of the loose central cuts.

Cut	Efficiency (%)
Had/EM	$100.0^{+0.0}_{-0.5}$
$I$	$97.3 \pm 0.5$
$E/p$	$95.0 \pm 0.7$
All cuts	$92.4 \pm 0.7$
Tracking, $E/p$ corrections	$99.2 \pm 0.4$
$c_2$ efficiency	$91.7 \pm 0.8$

tight cuts; a second electromagnetic cluster in central with  $E_T > 20$  GeV; a CTC (opposite sign) track pointing at a second cluster,  $P_T > 5$  GeV;  $I < 0.05$ , Had/EM  $< 0.05$  on first electron;  $81 < M_{e^+e^-} < 101$  GeV/ $c^2$ . There are 514 central-central  $Z^0$ 's satisfying these cuts. The efficiency of each of the tight central cuts  $c_1$  obtained from this sample is summarized in Table X. The net  $c_1$  efficiency, which, because of correlations between the cuts is not simply the product of the cut efficiencies, is  $85.1 \pm 1.1$  %.

There are two corrections to apply to the result for  $c_1$ . There is first an efficiency for the offline track reconstruction algorithm to reconstruct a track. This efficiency has been estimated by examining  $W$ 's which pass  $\not{E}_T$  triggers in level 2 and level 3.  $W$  candidates were selected by requiring  $E_T > 25$  GeV,  $\not{E}_T > 25$  GeV,  $L_{shr} < 0.2$ ,  $I < 0.1$ , and  $\sqrt{(\chi^2_{strip})^2 + (\chi^2_{wire})^2} < 20$ . Events with no three-dimensional track pointing at the cluster were counted as tracking failures. The tracking efficiency was found to be  $99.7 \pm 0.2$  %.

We also correct for a small  $E/p$  bias in our  $Z^0$  efficiency sample. In our  $Z^0$  efficiency sample, we require a track with  $P_T > 5$  GeV to point at the second cluster. This cut throws away real  $Z^0$ 's with  $E/p > 4$  from our efficiency sample. To estimate the magnitude of this effect, we scanned the  $Z^0$  events which failed the  $P_T > 5$  GeV cut on the second electron. We factor in an additional efficiency of  $99.5 \pm 0.3$  % as an estimate of this bias.

#### B. Loose central identification efficiency $c_2$

Using the same sample of Sec. VIII A, we find  $c_2 = 91.7 \pm 0.8$  %, as summarized in Table XI.

#### C. Loose plug identification efficiency $p$

To measure the efficiency of the plug electron identification efficiencies, we select central-plug  $Z^0$  events

TABLE XII. Efficiency of the loose plug cuts.

Cut	Efficiency (%)
Had/EM	$100.0^{+0.0}_{-0.3}$
$I$	$96.4 \pm 0.9$
$\chi^2_{3 \times 3}$	$95.2 \pm 1.1$
$p$ efficiency	$90.9 \pm 1.4$

TABLE XIII. Efficiency of the loose forward cuts.

Cut	Efficiency (%)
Had/EM	100.0 <sup>+0.0</sup> <sub>-1.8</sub>
$I$	85.9 $\pm$ 4.4
$f$ efficiency	85.9 $\pm$ 4.4

which pass the following cuts: One central leg that passes tight cuts; second electromagnetic cluster in plug with  $E_T > 15$  GeV; no other jets with  $E_T > 10$  GeV in the event;  $81 < M_{e+e-} < 101$  GeV/ $c^2$ ; Had/EM  $< 0.05$ ,  $I < 0.05$  on central electron; VTX occupancy  $> 0.5$  in octant pointing to plug cluster. There are 418 events passing these cuts. We find a  $90.9 \pm 1.4$  % efficiency (see Table XII).

#### D. Loose forward identification efficiency $f$

To measure the efficiency of the forward electron identification, we select a sample of central-forward  $Z^0$  events identical to the plug sample above, but this time with a forward electron with  $E_T > 10$  GeV and VTX occupancy  $> 0.25$ . There are 64 events passing these cuts. We find an efficiency of  $85.9 \pm 4.4$  % (see Table XIII).

#### E. Central electron trigger efficiency $\varepsilon_T$

The efficiency of the inclusive electron trigger in level 2 and level 3 is measured with  $W$ 's that pass the independent backup trigger that selects events based on  $\cancel{E}_T$  (see Sec. II G). A total of 10813 of our  $W$  candidates come in on the  $\cancel{E}_T$  triggers. Table XIV shows the efficiency results for level 2 and level 3.

The level 1 calorimeter trigger efficiency is estimated using a sample of muon + jet events that trigger the level 1 and level 2 muon triggers. The level 1 calorimeter trigger efficiency is determined from the fraction of jet(s) in these events that satisfy the calorimeter trigger. The level 1 calorimeter trigger is  $99.18 \pm 0.08$  % efficient for  $E_T > 12$  GeV (see Fig. 12).

#### F. Combined efficiencies $\varepsilon_W$ and $\varepsilon_Z$

Combining the results above, we compute the efficiencies  $\varepsilon_W$  and  $\varepsilon_Z$  for  $W$  and  $Z^0$  events to pass our electron selection. The  $W$  selection efficiency for electrons in the fiducial region is

TABLE XIV. Efficiency of the central electron trigger.

Trigger	Efficiency (%)
Level 1 trigger	99.2 $\pm$ 0.1
Level 2 trigger	91.5 $\pm$ 0.3
Level 3 trigger	98.2 $\pm$ 0.1
Total trigger eff., $\varepsilon_T$	89.2 $\pm$ 0.3

$$\varepsilon_W = \varepsilon_T c_1.$$

The  $Z^0$  efficiency is more complicated because the central-central  $Z^0$ 's have two chances for passing the inclusive electron trigger and because the selection criteria have slightly different efficiencies in the three detector regions. Considering only the central region, each leg has three possible outcomes: (a) it can pass tight cuts (see Table V) with probability  $\varepsilon_1 = \varepsilon_T c_1$ , (b) it can pass loose cuts (see Table VI) but not the tight cuts, with probability  $\varepsilon_2 = c_2 - \varepsilon_1$ , or (c) it can fail the loose cuts as well, with probability  $1 - c_2$ . Given that "tight"- "tight" and "tight"- "loose" combinations are accepted as candidates, the efficiency for central-central  $Z^0$ 's is  $(\varepsilon_1)^2 + 2(\varepsilon_1 \varepsilon_2)$ , or  $\varepsilon_T c_1 (2c_2 - \varepsilon_T c_1)$ . Thus the  $Z^0$  efficiency is

$$\varepsilon_Z = \varepsilon_T c_1 [F_{cc}(2c_2 - \varepsilon_T c_1) + F_{cp} + F_{cf} f],$$

where the fractions  $F_{cc}$ ,  $F_{cp}$ , and  $F_{cf}$  are the fractions of the  $Z^0$ 's in our acceptance which have one leg in the central region and the second in the central, plug, and forward, respectively. These fractions are determined with the Monte Carlo program described in Sec. VII. We find

$$\varepsilon_W = 75.4 \pm 1.0 \%,$$

$$\varepsilon_Z = 72.9 \pm 1.6 \%,$$

$$\varepsilon_W / \varepsilon_Z = 1.035 \pm 0.016 \%.$$

It is important to note that the factor  $\varepsilon_T c_1$  nearly cancels in the ratio  $\varepsilon_W / \varepsilon_Z$ , and thus the systematic error in  $\varepsilon_W / \varepsilon_Z$  is smaller than one gets adding the errors of  $\varepsilon_W$  and  $\varepsilon_Z$  in quadrature. This lower systematic uncertainty is one of the motivations for selecting a common tight central electron in measuring the ratio of the two cross sections.

### IX. CHECK OF THE RESULTS

The analysis for  $R$ , the  $W/Z^0$  cross-section ratio, has been presented in Secs. II-VIII, and the results will be presented in Sec. X. In this analysis, it has been stressed that many systematic effects tend to cancel in the ratio. These effects include the requirement of a common central electron, the kinematic criteria, and the lepton identification selection. It has also been stressed that the  $W$ 's require a larger background subtraction than do the  $Z^0$ 's. An important check of all these aspects of the result is provided by performing the entire analysis using an  $E_T$  cut on the first leg of  $E_T > 25$  GeV (for both  $W$ 's and  $Z^0$ 's), and a cut of  $\cancel{E}_T > 25$  GeV (for  $W$ 's). With these cuts, the number of background events to the  $W$ 's decreases, but Monte Carlo correction for the detector acceptances for  $W$ 's and  $Z^0$ 's increases. The comparison is shown below:

$$\frac{\sigma B(W \rightarrow e\nu)_{(20 \text{ GeV cuts})}}{\sigma B(W \rightarrow e\nu)_{(25 \text{ GeV cuts})}} = 0.992 \pm 0.003 \text{ (stat)}$$

$$\pm 0.008 \text{ (syst)},$$

$$\frac{\sigma B(Z^0 \rightarrow e^+e^-)_{(20 \text{ GeV cuts})}}{\sigma B(Z^0 \rightarrow e^+e^-)_{(25 \text{ GeV cuts})}} = 0.995 \pm 0.007 \text{ (stat)}$$

$$\pm 0.008 \text{ (syst)},$$

$$\frac{R_{(20 \text{ GeV cuts})}}{R_{(25 \text{ GeV cuts})}} = 0.995 \pm 0.008 \text{ (stat)}$$

$$\pm 0.011 \text{ (syst)},$$

where the statistical uncertainty in the ratios reflects only the statistically independent part of the two samples and the systematic uncertainty is only the additional uncertainty in the Monte Carlo that results from making higher kinematic cuts. The two measurements are complementary, since both the background and acceptance calculations are thus checked. The analysis with the 20 GeV cuts, however, has a smaller statistical uncertainty and an overall smaller systematic uncertainty, since the systematic uncertainty of determining the efficiency for the higher  $\cancel{E}_T$  cut offsets the smaller background uncertainties.

## X. CONCLUSIONS

Recall that the ratio of  $W$  and  $Z^0$  cross sections is given by the formula

$$R \equiv \frac{\sigma B(p\bar{p} \rightarrow W \rightarrow e\nu)}{\sigma B(p\bar{p} \rightarrow Z^0 \rightarrow ee)}$$

$$= \frac{\sigma(p\bar{p} \rightarrow W) \Gamma(W \rightarrow e\nu) \Gamma(Z^0)}{\sigma(p\bar{p} \rightarrow Z^0) \Gamma(Z^0 \rightarrow ee) \Gamma(W)}.$$

The background, efficiency, and acceptance results from the previous sections are summarized in Table XV. We find, for the ratio  $R$ ,

$$R = 10.90 \pm 0.32 \text{ (stat)} \pm 0.29 \text{ (syst)}.$$

In order to extract a value for the leptonic branching ratio of the  $W$  from the measurement of  $R$ , we use a theoretical calculation [36] of the ratio of production cross sections  $\sigma(p\bar{p} \rightarrow W)/\sigma(p\bar{p}) \rightarrow Z^0 = 3.35 \pm 0.03$ , together with the LEP [8] measurements of  $\Gamma(Z^0) = 2.4969 \pm 0.0038$  GeV and  $\Gamma(Z^0 \rightarrow e^+e^-) = 83.98 \pm 0.18$  MeV. We find, for the branching ratio,

TABLE XV. Summary of results for  $R$ .

	$W$ 's	$Z^0$ 's
Candidates:	13796	1312
Background:		
hadron jets	$898 \pm 155$	$20 \pm 9$
$W^\pm \rightarrow \tau^\pm \nu$	$473 \pm 29$	
$Z^0 \rightarrow \tau^+ \tau^-$	$48 \pm 7$	$1 \pm 1$
$Z^0 \rightarrow e^+ e^-$	$281 \pm 32$	
Heavy top	$0^{+40}_{-0}$	
Total background:	$1700^{+167}_{-163}$	$21 \pm 9$
Signal:	$12096 \pm 117^{+163}_{-167}$	$1291 \pm 36 \pm 9$
Acceptance:		
$A_{W,Z}$	$0.342 \pm 0.008$	$0.409 \pm 0.005$
$A_W/A_Z$	$0.835 \pm 0.013$	
$F_{cc}$		$0.372 \pm 0.007$
$F_{cp}$		$0.509 \pm 0.007$
$F_{ct}$		$0.120 \pm 0.004$
Efficiencies:		
$\epsilon_{TC1}$	$0.754 \pm 0.011$	$0.754 \pm 0.011$
$c_2$		$0.917 \pm 0.008$
$p$		$0.909 \pm 0.014$
$f$		$0.859 \pm 0.044$
$\epsilon_{W,Z}$	$0.754 \pm 0.011$	$0.729 \pm 0.016$
$\epsilon_W/\epsilon_Z$	$1.035 \pm 0.016$	
Drell-Yan correction		$1.005 \pm 0.002$
$\sigma(W \rightarrow e\nu)/\sigma(Z \rightarrow ee)$	$10.90 \pm 0.32 \text{ (stat)} \pm 0.29 \text{ (syst)}$	

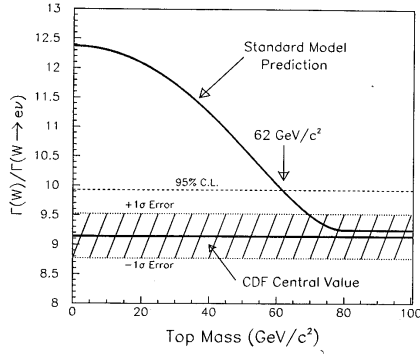


FIG. 40.  $B(W \rightarrow e\nu)^{-1}$  vs  $M_t$ . As the top mass increases toward the  $W$  mass, the phase space for the decay  $W \rightarrow t\bar{b}$  is reduced.

$$\Gamma(W \rightarrow e\nu)/\Gamma(W) = 0.1094 \pm 0.0033 \text{ (stat)} \\ \pm 0.0031 \text{ (syst)}.$$

The standard model prediction [5] assuming  $m_t > M_W - m_b$  is  $0.1084 \pm 0.0002$ .

In order to set a model-independent limit on the top mass, we use the “inverse” branching ratio since its uncertainty is more nearly Gaussian:  $\Gamma(W)/\Gamma(W \rightarrow e\nu) = 9.14 \pm 0.28 \text{ (stat)} \pm 0.26 \text{ (syst)}$ . As the mass of the top quark increases toward the  $W$  mass, the partial width  $\Gamma(W \rightarrow t\bar{b})$  goes to zero, and the ratio  $\Gamma(W)/\Gamma(W \rightarrow e\nu)$  approaches the standard model value of 9.225. In Fig. 40 we plot our value for  $\Gamma(W)/\Gamma(W \rightarrow e\nu)$  along with the expected curve as a function of top quark mass. We establish the limit [37]

$$m_t > 62 \text{ GeV}/c^2 \text{ (95\% confidence level)}.$$

We emphasize again that this limit is independent of models of the top quark’s allowed decay modes, providing the  $W$  can decay with normal coupling to  $t\bar{b}$ . Previous direct searches for the top have either assumed that the top quark must decay only via  $Wb$  [1,2], or assumed particular Higgs boson decay modes, which can depend upon the parameter  $\tan\beta$  [3].

With the present measurement of the  $W$  leptonic branching ratio and the previous direct measurement [15] by CDF of the total width,  $\Gamma(W) = 2.11 \pm 0.32 \text{ GeV}$ , we may extract a measurement of the  $W$ -fermion coupling  $g$  at  $Q^2 = M_W^2$  (see Sec. I). We combine the two to obtain  $\Gamma(W \rightarrow e\nu) = 231 \pm 36 \text{ MeV}$ , and assuming  $\Gamma(W \rightarrow l\nu) = \frac{g^2 M_W}{48\pi}$  and using the world average [38] for the  $W$  mass,  $M_W = 80.23 \pm 0.18 \text{ GeV}^2$ , we find

$$g = 0.659 \pm 0.052.$$

Note that the standard model expectation is  $g^2 =$

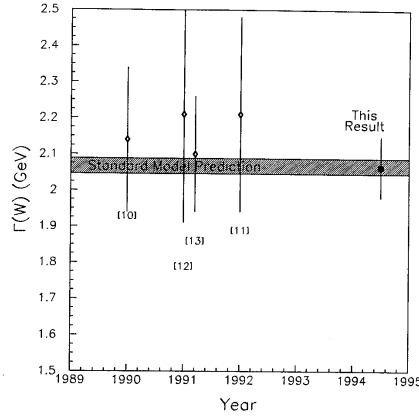


FIG. 41. Previous measurements of  $\Gamma(W)$ , along with the present measurement.

$\frac{8}{\sqrt{2}} G_F M_W^2 = 0.425 \pm 0.002$ , or  $g = 0.652 \pm 0.001$ . The leptonic partial width  $\Gamma(W \rightarrow e\nu)$  is preferable to quark widths for extracting a value of  $g$ , since it does not receive any QCD corrections and it is not sensitive to uncertainties in Cabibbo-Kobayashi-Maskawa matrix elements.

If we assume the standard model value of  $g$ , we can calculate the  $W$  leptonic partial width  $\Gamma(W \rightarrow e\nu) = 225.9 \pm 0.9 \text{ MeV}$  and obtain a value for  $\Gamma(W)$  from the branching ratio measurement:

$$\Gamma(W) = 2.064 \pm 0.060 \text{ (stat)} \pm 0.059 \text{ (syst)} \text{ GeV}.$$

It must be emphasized, however, that this value for  $\Gamma(W)$  is not sensitive to  $g$ . The standard model prediction [5] assuming  $m_t > M_W - m_b$ , is  $\Gamma(W) = 2.067 \pm 0.021 \text{ GeV}$ . Figure 41 shows this measurement of  $\Gamma(W)$  in comparison to previous measurements.

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